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A PREDESIGN REPORT ON

MARINE WASTE DISPOSAL

VOLUME I

DEPT. OF
PUBLIC WORKS

CITY AND COUNTY OF SAN FRANCISCO

BROWN AND CALDWELL
CONSULTING ENGINEERS
SAN FRANCISCO

SEPTEMBER
1971

CITY AND COUNTY OF SAN FRANCISCO

A PREDESIGN REPORT ON

MARINE WASTE DISPOSAL

VOLUME I

OCEANOGRAPHIC AND ECOLOGICAL BASE DATA ACQUISITION AND EVALUATION OF ALTERNATIVE LOCATIONS.

SEPTEMBER, 1971

BROWN AND CALDWELL
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PREDESIGN REPORT ON MARINE WASTE DISPOSAL

In accordance with our agreement for engineering services dated June 23, 1969, we submit herewith the final report on our studies of the feasibility of marine waste disposal in the waters of San Francisco Bay and the Pacific Ocean adjacent to the city. The report is presented in two volumes. Volume I contains the text of the report, together with explanatory graphs, tables and figures. Volume II presents the data which were collected in the course of the study, together with special reports on specific phases of the study program.

The basic finding of our two-year study is that primary effluent from the City of San Francisco, discharged at appropriate points through properly designed submarine diffusers, will not adversely affect the marine environment of the Central Bay or the Gulf of the Farallones.

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CHAPTER 1

INTRODUCTION

For over 100 years San Francisco has discharged its sewage to the adjacent waters of San Francisco Bay and the Pacific Ocean. For more than 70 years the discharges consisted of raw sewage, completely untreated. Shortly before World War II, however, a growing community concern for the quality of the environment, particularly along the popular and attractive ocean beaches, led San Francisco to construct the first major sewage treatment plant built in the San Francisco Bay Area. Constructed in the western end of Golden Gate Park, the Richmond-Sunset plant continues to serve the residential areas from which it draws its name.

Within the last two decades a continuing program of sewerage improvements has achieved its initial goal of complete interception and treatment of all dry weather sewage discharges. Three major treatment plants now provide primary treatment and disinfection of all San Francisco dry weather sewage flows prior to discharge to the adjacent receiving waters. The problem of wet weather sewage flows, vastly complicated by the fact that the city has developed with a system of sewers which carry combined sanitary sewage and storm runoff, remains to be solved.

Beginning in 1964 a massive study effort was undertaken by the State Water Resources Control Board. Its goals were the definition of the present condition of San Francisco Bay and the development of a program to guarantee preservation of the bay as a great natural asset to the entire area. The study effort culminated in the publication in 1969 of the San Francisco Bay-Delta Water Quality Control Program, which presented recommendations for water quality control measures to be instituted throughout the entire bay system. The report is notable for the fact that an attempt was made to consider the ecology of the entire bay and the adjacent ocean waters in establishing criteria for waste disposal.

By 1969 a number of factors had combined to raise major questions regarding the future course of San Francisco's long-range planning for the disposal of sewage effluents and storm drainage. The most significant of these factors are:

1. An explosive growth of concern for the environment in the last few years has focused attention on waste disposal and its effect on water quality in San Francisco Bay and the Pacific Ocean. The state and regional water quality control agencies have reflected this concern by establishing increasingly restrictive requirements for the discharge of wastes to the receiving waters. As a result, all three of San Francisco's sewage treatment plants are presently in violation of discharge requirements. At the same time the control agencies have shortened the time which the city is allowed to bring its discharges into compliance. The Regional Water Quality Control Board now requires compliance with the new requirements by January 1973.

2. The Bay-Delta Water Quality Control Program recommends as a long-range solution the transport of all domestic and industrial wastes from the central and south bay areas, including San Francisco, to a regional plant located in Redwood City. Treatment would be followed by deep water disposal in the Pacific Ocean west of San Gregorio.

3. Because of their volume, San Francisco's wet weather flows must be disposed of locally regardless of the plan which is adopted for the long-range disposal of dry weather sewage flows.

4. The initial measures which are taken to bring the city's dry weather discharges into compliance by 1973 must be consistent with the goals of sound long-range planning, and insofar as can be determined must represent the most economical course of action for the city.

Other Studies

In addition to the investigations which are described in this report, four other studies have provided information of major importance to the solution of the problem of waste disposal for the City of San Francisco. Each of these studies is summarized briefly below.

A Comprehensive Study of San Francisco Bay. Undertaken by the Sanitary Engineering Research Laboratory of the University of California at Berkeley as contractor to the State Water Resources Control Board, the report entitled "A Comprehensive Study of San Francisco Bay"[1] was published in seven volumes in 1965, 1966 and 1967. The report contains the most complete physical, chemical, hydrological, and biological data ever assembled on the entire San Francisco Bay system. This report represents a principal reference for any detailed study of the characteristics of a local area of San Francisco Bay.

San Francisco Bay-Delta Water Quality Control Program. Kaiser Engineers, acting as master contractor, undertook the studies in 1966 which culminated in publication of the Bay-Delta Water Quality Control Program[2] three years later. The report was commissioned by the California State Legislature and directed by the State Water Resources Control Board. The report set forth water quality objectives which were in many respects more restrictive than those in force at the time, and introduced relative toxicity as a water quality control parameter. The recommended water quality control plan proposed that the City of San Francisco take no action before 1980 other than improvement of treatment as necessary.

The State Legislature at the time this report was written had not adopted legislation to create the regional agency which will be required to implement the plans set forth in the recommended water quality control system. The State Water Resources Control Board has, however, commissioned additional studies to define and clarify the concept of toxicity as a water quality control parameter.

Alternative Methods of Effluent Disposal. In 1968 the City and County of San Francisco commissioned the firm of Brown and Caldwell to investigate the costs of alternative methods for the disposal of treated effluent from the city's three treatment plants. The report[3] compared seven plans for achieving water quality objectives and concluded that primary treatment followed by deep water discharge represents the most economical method of satisfactorily disposing of dry weather sewage flows. The report was published shortly before the San Francisco Bay-Delta Water Quality Control Program was released.

Water Pollution Control Plant Study. In June of 1970 the City and County of San Frnacisco, through its Department of Public Works, in response to the 1969 requirements of the San Francisco Bay Regional Water Quality Control Board, engaged the firm of Brown and Caldwell to prepare engineering reports evaluating present performance and developing costs for different levels of effluent quality improvement for each of its three water pollution control plants. In addition to studying plant improvements, the reports will include a determination of the assimilative and dispersive capacity and background quality of the receiving waters for the Southeast plant. It is expected that the results of the water pollution control plant study, in combination with the results of the predesign study of submarine outfall sewers, will provide the city with sufficient information to enable selection of the most satisfactory method for meeting discharge requirements. Preliminary drafts of Reports 1 and 2 of Phase I of the water pollution control plant study were completed and submitted to the city for review during December 1970. These reports cover the evaluation of plant performance and process changes necessary to achieve various levels of improvement in effluent quality. All study reports were scheduled for completion by the end of 1971.

Objectives and Scope of Present Study

In 1969 the City of San Francisco found itself faced with the necessity of bringing its dry weather discharges to San Francisco Bay into compliance with revised requirements by 1975. The latter date was advanced to January 1973 by the State Water Resources Control Board a few months later. Recognizing the need for additional information to permit the city to meet its immediate obligations in a manner consistent with sound long-range planning, the Director of Public Works engaged the firm of Brown and Caldwell to make the necessary engineering investigations and present a predesign report. Under an agreement dated July 9, 1969, the work covered by the study included two basic phases:

1. Development of preliminary designs for submarine outfalls into San Francisco Bay and the Pacific Ocean for disposal of effluents discharged from the North Point and Richmond-Sunset Water Pollution Control Plants.
2. Development of information on suitable submarine disposal sites as necessary to define the degree of treatment required prior to discharge of intermittent overflows from combined sewers into San Francisco Bay and the Pacific Ocean between Bay Street extended and Lincoln Way extended.

The agreement further stated that the results of the study, as submitted in the final report, must be consistent with the requirements and policies of the following governmental agencies:

Regional Water Quality Control Board
San Francisco Bay-Delta Water Quality Control Program
Bay Conservation and Development Commission
San Francisco Board of Supervisors

The primary objectives of the oceanographic study, and their relationship to the policies of the controlling agencies and to the requirements for design, were described in the Scope of Work. With the advice and consultation of the city's advisory boards, the Scope of Work was set forth in detail as follows:

1. **Definition of the Current Regimen.** In order to determine the direction and rate of movement of an effluent field, the velocity and direction of currents must be established. Since the currents in the area under study are primarily tidal, observations must cover a complete range of tidal conditions as well as conditions representative of both high and low outflow from the San Francisco Bay system. Particularly during periods of high outflow from the bay, it is possible that currents may be substantially different at the surface and at depths near the bottom. Currents will be measured at different depths to assess this possibility. Information on tidal currents is also necessary to determine the mass movement of water past the candidate disposal sites. A knowledge of mass displacement is useful in an assessment of the possibility of waste concentrations increasing due to pollutional buildup over a series of tidal cycles.

In conjunction with current measurements, mass water movements in approximately a 100 square mile area outside the Golden Gate will be established by use of aerial photography techniques. The pattern of outflow from San Francisco Bay can be recorded on infra-red color reversing film by virtue of the difference in turbidity between the bay and ocean waters.

2. **Determination of Water Density Versus Depth.** Prediction of the behaviour of a marine waste discharge is dependent on a knowledge of the relationship between receiving water density and water depth. Receiving water density is a function primarily of temperature and salinity. Under stratified conditions of temperature or salinity, or both, a waste discharge may remain submerged rather than rising to the surface of the receiving waters. Density stratification may result from summer warming of the surface layers or from the surface outflow of low salinity water during periods of high outflow from the bay system. To establish whether density stratification exists, temperature and salinity will be measured at various depths over a complete range of tidal conditions and at different seasons of the year. Measurements will cover all areas of interest for ocean outfall construction.

3. **Determination of Dissolved Oxygen.** Compliance with Water Quality Control Board requirements for dissolved oxygen is judged in part by the deviation of dissolved oxygen from natural background levels. It is important that as much information as possible be developed on natural levels of dissolved oxygen prior to the initiation of a waste discharge to establish the pre-existing condition with respect to dissolved oxygen.

4. **Determination of Dispersion Coefficients.** Once a discharged effluent has reached stability with the receiving water, further dilution is achieved through dispersion in the water mass. Dispersion results from eddies and boils in the receiving water mass, and may occur in both the horizontal and vertical planes. Prediction of the rate of dispersion of the effluent field is essential to the prediction of receiving water quality at any point removed from the immediate vicinity of the discharge. Since dispersion coefficients will be a function of currents and turbulence, and since currents in the projected disposal areas are primarily tidal, it will be necessary to determine dispersion coefficients at different tidal stages.

5. **Observations of Surface Drift.** Receiving water quality criteria prohibit the presence of floating material of waste origin in areas protected for recreational use, and treatment prior to discharge puts heavy emphasis on the removal of floatable material. All other factors being equal, the preferred site for a submarine outfall will be the one from which escaped floatables are least likely to find their way into recreational waters or other sensitive areas. The direction of surface drift is therefore another useful factor in the evaluation of a proposed submarine disposal site. Surface drift is a surface film phenomenon which is primarily wind-induced. There may be no relationship between direction of surface drift and mass water movements as measured by tides and currents, and it is therefore necessary to make separate observations to characterize surface drift.

6. **Determination of Ecological Conditions.** One of the primary considerations in submarine disposal of sewage effluents is that such disposal be accomplished in a manner that insures no damage to the marine environment. Since the area outside the Golden Gate is important to the mar-

ket crab fishery, the effect of sewage effluent discharges on crab larvae and adult crabs will be determined. Studies will be conducted of the benthos in the area, and effects of existing sewage discharges along the West Coast will be evaluated.

7. **Determination of Bay-Ocean Interchange.** The ability of San Francisco Bay to accept sewage discharges with no deleterious effects is dependent in part on the rate at which bay water is flushed out to the ocean on each tidal cycle. This in turn is dependent on the amount of new ocean water brought into the bay on each flood tide. Seasonal temperature conditions are such that the temperature difference between bay and ocean waters in the late summer can be used to compute the tidal interchange between the bay and ocean.

8. **Definition of Bottom Conditions.** Bottom conditions will be surveyed in the area proposed for the construction of submarine outfall lines. Bottom topography and the type of bottom materials in the disposal areas will be determined to establish the final location of the outfalls and to provide information for the design of such features as the pipe ballasting or anchorage system.

Advisory Boards

Two advisory boards were inpaneled by the city to offer advice and direction throughout the course of the study. The first, identified as the Technical Advisory Board, consisted of recognized authorities in the fields of environmental engineering, oceanography, and marine ecology. Serving as Chairman of the Technical Advisory Board was Percy H. McGauhey, Professor Emeritus of Sanitary Engineering at the University of California, Berkeley. Other members included Dr. Pat Wilde, Professor of Oceanography at the University of California, Berkeley; Dr. Wheeler J. North, Professor of Marine Biology at California Institute of Technology; and Dr. Curtis L. Newcombe, Professor of Biology at San Francisco State College. The members of the Technical Advisory Board, individually and as a group, played a major role in the formulation of the scope of work and the detailed work program for the study. In addition, they provided valuable advice and direction throughout the conduct of the study and during the preparation of this report.

The second group, the Project Advisory Board, was composed of representatives of those agencies which are actively concerned with the outcome of the study. The Project Advisory Board included representatives of the following organizations and public agencies:

State of California Department of Public Health, Bureau of Sanitary Engineering
State of California Department of Fish and Game
Environmental Protection Agency
U. S. Army Corps of Engineers, San Francisco District
San Francisco Bay Conservation and Development Commission
Marin Municipal Water District
San Mateo County Engineer's Office
North San Mateo County Sanitation District

The State Water Resources Control Board and the Regional Water Quality Control Board were also invited to send representatives to the Project Advisory Board. Because of their position as water quality control agencies, however, they elected to assume the role of observers rather than members of the Board. The Project Advisory Board took an active and constructive part in the direction of this study, particularly through its review and criticism of the scope of work and the work program as developed by Brown and Caldwell and the Technical Advisory Board.

Extent of Study Area

A proper study of marine disposal of sewage effluents must define as accurately as possible the characteristics of the receiving waters which will be affected by the discharge. Since the area affected depends at least in part upon the oceanographic characteristics of the waters to be studied, the boundaries of the study area must be defined as the study progresses. At the start of the study it was postulated that any determinable effect of waste discharge would not extend beyond the limits of a single tidal excursion from the bay into the ocean, or a single tidal incursion from the ocean into the bay. Depending on the season of the year, these limits were found to encompass the Central Bay and most of the Gulf of the Farallones. For purposes of this study, the Gulf of the Farallones is defined as that portion of the Pacific Ocean which extends from Bolinas Peninsula on the north to Point Montara on the south, and from the Golden Gate to Southeast Farallon Island. Those portions of the study area which might be significantly affected by a waste discharge are of course much smaller and confined to the immediate area of the discharge. Particular attention was given to the latter areas.

Information and Data Available to Survey.

Full use was made of previous studies and reports prepared for the City of San Francisco and for other local, state and federal agencies. Additional information was obtained from the State Department of Fish and Game, the Regional Water Quality Control Board, the U. S. Army Corps of Engineers, the U. S. Geological Survey, and the U. S. Coast and Geodetic Survey.

Information on wastewater flows and characteristics was supplied by the City of San Francisco. Size and location of sewer lines were taken from city maps and verified by field check where necessary.

Literature and other references cited by superscript in the text of the report are listed in Appendix A. Unnumbered references listed in Appendix A were used as sources of background material but are not specifically referred to in the text. For simplicity, abbreviations have been used in this report for many technical and nontechnical terms. Each abbreviation is defined where it first appears, and all abbreviations are listed alphabetically in Appendix B.

Acknowledgments

Successful completion of a study of this type is dependent on the advice and cooperation of a great many individuals and organizations. We are particularly indebted to Robert C. Levy, San Francisco City Engineer, and his competent staff for their advice, assistance and wholehearted cooperation. The direction and guidance of the city's Technical Advisory Board has been invaluable, and we wish to express our gratitude to Professor P. H. McGauhey, Chairman, and to Dr. Curtis L. Newcombe, Dr. Wheeler J. North, and Dr. Pat Wilde, the members of the Board.

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CHAPTER 2

EXISTING SEWERAGE SYSTEM

The first sewers were constructed in San Francisco about the year 1850, but it was not until the end of the century that the first comprehensive study was made of the city's sewerage needs. Construction of a planned system of trunk sewers and interceptors began about 1910, and that system is for the most part still in service today. Though foresighted in their plans for a conveyance system, the planners of that time failed to foresee the future need for sewage treatment, The trunk sewers were constructed to carry both sanitary sewage and storm water, and were run by the most direct route to the waterfront, where the wastes were discharged raw into the bay and ocean. The construction of a city-wide sewerage system therefore resulted in gross pollution of the adjacent waters.

Conditions in 1935 were summarized in a report by a board of consulting sanitary engineers[4] as follows: "The shore waters of the City and County of San Francisco are more or less polluted with sewage throughout their entire length from the southeast boundary around to the southwest city limit. The presence of sewage is shown by fecal matter and other litter along the beaches and is demonstrable in the coastal waters at nearly all points by laboratory tests." That report recommended the construction of three sewage treatment plants. The first was placed in operation in 1938. Completion of the second and third plants in 1951 provided sufficient treatment capacity to serve the entire city during dry weather, but it was not until 1966 that the final diversions were made to deliver all of the dry weather sewage flow to the treatment plants.

Sewage Collection System

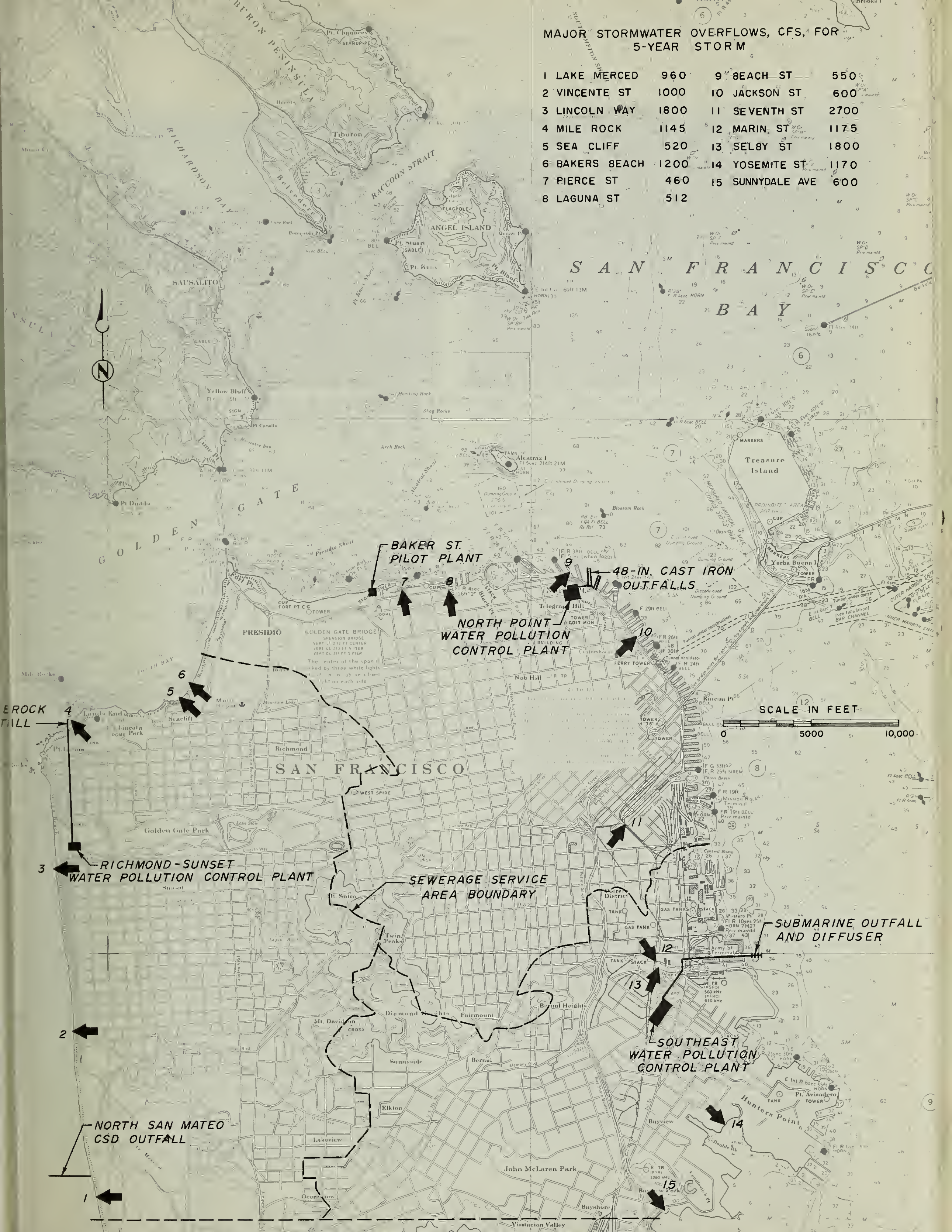
The problems associated with a sewerage system which conveys both sanitary sewage and storm runoff are shared by many cities that developed their sewerage systems around the turn of the century. Since the runoff from a major storm may cause rates of flow in the sewers which are more than 100 times as great as normal dry weather sewage flow, a combined sewerage system quite obviously creates some special problems in treatment and disposal.

A description of the sewerage system and the storm water overflow points is contained in a 1967 report by Engineering-Science, Inc.[5] That report also describes the strength and volume characteristics of the storm water overflows and discusses methods of treatment. Since the design and operation of the collection system is beyond the scope of this report, it need not be further dealt with here.

Sewage Treatment and Disposal System

The entire City of San Francisco is divided into three sewerage service areas, each of which is served by a primary treatment plant (Fig. 2-1). For the purposes of this report the names of the sewage treatment plants also identify the drainage areas they serve. The three plants are known as the Richmond-Sunset, North Point and Southeast Water Pollution Control Plants. The present mode of operation provides for the interception, conveyance and treatment of sewage flows up to about three times the average dry weather flow. Flows in excess of that amount are bypassed directly to the receiving waters at a number of points along the waterfront as shown in Fig. 2-1.

Richmond-Sunset Plant. The Richmond-Sunset Water Pollution Control Plant was the first of the city's three plants, and now serves the entire western slope of the city. Situated in the western end of Golden Gate Park, the plant has a peak hydraulic capacity of 70 mgd (million gallons per day) and presently treats an average dry weather flow of about 20 mgd. First constructed in 1938, and subsequently expanded to its present capacity, the Richmond-Sunset plant is a primary treatment plant of conventional design. The principal treatment units include four grit and grease removal tanks with a detention time of about seven minutes at present average dry weather flow, five sedimentation tanks with a detention time of two hours and an overflow rate of 900 gpd/sq ft (gallons per day per square foot) at average dry weather flow, and two sludge digesters with a total capacity of 424,000 cu ft (cubic feet). At present dry weather flows, the plant is operating at a BOD (biochemical oxygen demand) removal



MAJOR STORMWATER OVERFLOWS, CFS, FOR 5-YEAR STORM

1	LAKE MERCED	960	9	BEACH ST	550
2	VINCENTE ST	1000	10	JACKSON ST	600
3	LINCOLN WAY	1800	11	SEVENTH ST	2700
4	MILE ROCK	1145	12	MARIN ST	1175
5	SEA CLIFF	520	13	SELBY ST	1800
6	BAKERS BEACH	1200	14	YOSEMITE ST	1170
7	PIERCE ST	460	15	SUNNYDALE AVE	600
8	LAGUNA ST	512			

Fig. 2-1 Existing Sewage Treatment and Disposal Facilities

Effluent from the Richmond-Sunset Water Pollution Control Plant is visible in the ocean near the discharge point at Lands End.

Effluent from the North Point Water Pollution Control Plant, discharged at the ends of Piers 33 and 35, at times discolors the water of the bay for more than a mile along the shoreline.

efficiency of 37 percent and a suspended solids removal efficiency of 62 percent.

Chlorinated effluent from the Richmond-Sunset Water Pollution Control Plant is discharged to the 9 ft by 11 ft Mile Rock outfall sewer, which tunnels under Fort Miley and Lincoln Park and discharges to the beach at Lands End about 1.3 ft below mean lower low water. During wet weather the Mile Rock outfall also carries untreated storm water from combined sewers within the Richmond-Sunset drainage area.

North Point Plant. The North Point Water Pollution Control Plant serves the main downtown section of San Francisco. Completed in 1951, the plant is situated on Bay Street between the foot of Telegraph Hill and the Embarcadero. Present peak hydraulic capacity of the plant is about 160 mgd, and it is presently operating at an average dry weather flow rate of 60 mgd. Principal treatment units include manually and mechanically cleaned bar screens in series, four grit removal channels, an influent pumping station with a total installed pumping capacity of 190 mgd, and six preaeration-sedimentation tanks with a detention time of 2.8 hours and an overflow rate of 1100 gpd/sq ft at present dry weather flow rates. Sludge and scum removed by the sedimentation process are not further processed at the North Point plant, but instead are pumped through a 10-inch force main to the Southeast Water Pollution Control Plant for digestion and disposal. The North Point plant is presently operating at a BOD removal efficiency of about 39 percent and suspended solids removal efficiency of 64 percent, based on dry weather flows.

After chlorination the effluent from the North Point plant is conveyed to four 48-inch cast-iron effluent lines, two of which are laid beneath Pier 33 and two beneath Pier 35. The lines terminate without diffusers about 800 ft offshore and 10 ft below mean lower low water. Normally, the cast-iron effluent lines carry only treated plant effluent. Storm water is bypassed to the bay at other points.

Southeast Plant. The Southeast Water Pollution Control Plant, which went into operation in 1951, is perhaps best considered as two separate plants constructed side by side. The first section of the plant provides conventional primary treatment for the sewage flow from the Southeast drainage area as shown on Fig. 2-1. The second section of the plant consists of the sludge digestion and processing facilities, which handle not only the sludge from the Southeast plant itself but also the sludge transferred from the North Point plant. The two sections are located side by side in the industrial area south of Islais Creek channel between Third Street and the Southern Pacific right-of-way.

The primary treatment facilities at the Southeast plant are designed for a peak flow rate of 70 mgd, about twice the present maximum dry weather flow. Dry weather flow presently averages 18 mgd. The principal treatment units include hand-cleaned and mechanically-cleaned bar screens in series, two grit removal channels, an influent pumping station with an installed capacity of 70 mgd, and four preaeration-sedimentation tanks with a total detention time of 4.6 hours and an overflow rate of 630 gpd/sq ft at average dry weather flow. Raw sludge from the sedimentation tanks is pumped to the adjacent sludge digesting and processing plant. Despite the fact that the primary treatment facilities are very lightly loaded in terms of detention time and overflow rate, plant efficiency is only fair. During periods of dry weather the plant removes on the average 28 percent of the BOD and 32 percent of the suspended solids in the raw sewage. These low efficiencies are caused primarily by the carry-over of solids from the sludge processing plant. Deficiencies in sludge processing were being corrected as this report was written.

Raw sludge from both the Southeast plant and the North Point plant is pumped to the sludge processing section of the Southeast plant. There the sludge passes through sludge thickening tanks and the thickened sludge is transferred to digestion tanks. The plant contains 10 digestion tanks with an aggregate capacity of 2.4 million cubic feet, about twice the capacity that is presently needed. The digested sludge is elutriated, conditioned with ferric chloride, and dewatered on vacuum filters. The filter cake, along with grit and screenings from primary treatment, is hauled to sanitary landfill.

After chlorination, plant effluent flows to a pumping station on the south side of Islais Creek. From this point the effluent may either flow by gravity or be pumped to a submarine outfall which extends about 800 ft offshore of the Army Street terminal. A 300-ft long diffuser section located about 40 ft below mean lower low water provides a minimum initial dilution of about 50 to 1.

Wet Weather Flows. At the present time sewage flows resulting from a rainfall in excess of 0.02 inches per hour are bypassed directly to the bay and ocean at 41 diversion structures along the city's shoreline. However, several of these overflows are minor or are grouped in a single area. Most of the overflow occurs at 15 principal points described by Engineering-Science, Inc. in a 1967 report[5]. The locations of these points and the approximate quantities of overflow for a storm with a 5-year frequency of occurrence are shown on Fig. 2-1.

The Regional Water Quality Control Board declared in 1968 that the uncontrolled discharge of wet weather flows is no longer acceptable, and that treatment will be required as necessary to meet certain minimum standards of receiving water quality. The massive quantities of flow involved and the dispersion of discharge points along a 23-mile shoreline pose obvious technical and financial problems. To find the best solutions the city has undertaken major study programs in three principal areas. Unfortunately, the final results were not available in any of the three areas at the time this report was written, and certain recommendations of this report must remain tentative until the results of the study programs are available. The areas of study are as follows:

1. Flow conveyance and storage. Since the wet weather flows can no longer be discharged to the receiving waters directly, all of the present overflow points must be intercepted and the flows conveyed to centrally located treatment facilities. Some scheme for storage must be employed to reduce the peak flows to manageable quantities.

2. Treatment of sewer overflows. Because the storm flows in combined sewers have characteristics different from dry weather sewage flows, the problems of treatment are different. Reference 5 developed the characteristics of combined sewer overflows and suggested methods of treatment. Based on the recommendations in that report a dissolved air flotation pilot plant was built on the Baker Street sewer overflow line. The pilot plant will supply information on the treatability of storm overflows by the air flotation method and will aid materially in the evaluation of treatment costs.

3. Capability of present treatment plants. Concurrent with this study, Brown and Caldwell was investigating the three existing water pollution control plants to determine their maximum capability under various modes of operation. One of the results of this study will be a determination of the peak rate at which storm flows can be treated in the existing plants, thus defining by difference the amount of new treatment capacity which is required.

CHAPTER 3

SEWAGE DISPOSAL REQUIREMENTS AND METHODS

Each time a community undertakes the obligation to provide sewage service for its residents, it assumes the attending obligation to dispose of the sewage in a manner which will protect the public health, prevent nuisance conditions, and maintain receiving water quality consistent with beneficial uses. These conditions determine the degree and often the type of treatment which must be provided prior to disposal and strongly influence the selection of a disposal point. Disposal requirements frequently affect the relative economy and in some cases the feasibility of alternative sewerage projects.

GOVERNMENT REQUIREMENTS AND POLICY

Disposal of sewage and industrial wastes is regulated in California by regional water quality control boards. There are nine such boards in the state, each of which is responsible for establishing sewage disposal requirements and water quality objectives within its own topographic region. The San Francisco area is under the jurisdiction of Regional Water Quality Control Board No. 2, with headquarters in Oakland. Although the regional boards coordinate the interests of all local and state agencies, the state and local departments of public health retain special powers in cases where water contamination involves a significant hazard to public health. The regional boards have rather broad enforcement powers, which include the levying of fines and jail sentences against polluters after proper legal and administrative procedures have been followed.

Under the terms of the Federal Water Pollution Control Act, the State of California has adopted water quality objectives for interstate and navigable waters within the state. With minor exceptions the state objectives have been accepted by the Environmental Protection Agency, and are now identified as federal water quality standards. The federal government has rather limited but effective powers for the enforcement of compliance with the standards. Most effective is the power to withhold federal grants-in-aid. Since most sewage treatment and disposal projects for the City of San Francisco would be eligible for federal grants of from 30 to 55 percent of construction cost, the federal standards are enforced by the power, in effect, to assess penalities which might run into many millions of dollars. In the San Francisco area, where pollution would affect only the residents of the State of California, the federal government cannot bring legal action against a polluter without the written consent of the Governor.

The agreement for engineering services between Brown and Caldwell and the Director of Public Works, which covers the conduct of this study, states that the recommendations of this report shall comply not only with the requirements and policies of the Regional Board, but also with the water quality objectives of the Bay-Delta Program Bay-Delta water quality objectives and federal water quality standards are considered where they are more restrictive than those of the Rgeional Board.

Discharge requirements establish the legal basis for the day-to-day regulation of a specific discharge, and may be expected to change as the Regional Board pursues its long-range policy goals. Policy objectives are a statement of the long-range policy goals of the regulatory agencies, and in some cases are more restrictive than the presently enforced requirements, In any case, both requirements and policy goals are aimed at protecting the public health and the beneficial uses of the receiving waters.

Protection of Public Health

Disastrous human experience has amply demonstrated that sanitary sewage constitutes one of the primary vehicles of infection. It follows, therefore, that proper collection and safe disposal of this waste are essential to the protection of public health. The potential hazard to public health is judged and measured by (a) the proximity to sources of human waste discharges, either continuous, intermittent, or accidental, and (b) the number of coliform group organisms present in the water, usually expressed as the MPN (most probable number) per 100 ml (milliliters). Members of this group, though generally not pathogenic or disease-producing, are present in immense numbers in the fecal discharges of all warm-blooded animals, including man. Since this group as a whole is readily cultured and identified, these organisms are a useful indicator of the potential presence of pathogenic bacteria of sewage origin.

In the case of waters used for recreational purposes, very little evidence is available which relates the degree of coliform contamination to the incidence of water-borne disease. As a result, standards of governmental agencies pertaining to water-contact sports are far from consistent, ranging in limits from an MPN of 240 to 2400 per 100 ml. Further, these are variously expressed as the arithmetic mean, median, or geometric mean of a series of samples, or in some cases as the maximum for a single sample. It is evident, therefore, that a specific coliform limit does not define a line between a safe and a hazardous water, but rather is intended as a desirable and, presumably, attainable goal. The California Administrative Code, Title 17, Public Health, states that for salt waters the bacteriological limit for public beaches and water-contact sports areas is an MPN of 1000 per 100 ml or less in 80 percent of the samples analyzed. The San Francisco Bay Regional Water Quality Control Board requires a median MPN of 240 per 100 ml, which is an approximate statistical equivalent of the Title 17 requirement.

Sanitary provisions applying to waters where shellfish are taken for human consumption are considerably more restrictive than those for recreational areas. Shellfish act as efficient concentration mechanisms for bacteria and certain other contaminants, such as radioactive wastes. Numerous disease outbreaks have been traced to the consumption of raw shellfish grown in polluted waters, The U. S. Public Health Service[6] has established a bacteriological standard calling for a median MPN of not more than 70 per 100 ml for approved commercial shellfish growing areas. It is well established that shellfish from waters meeting this standard will not be involved in the spread of disease which can be attributed to initial contamination of the shellfish, provided that the growing area is also protected against chance contamination with fecal material. Standards for commercial shellfish growing areas are frequently applied as well to areas which are to be protected for sport shellfishing.

Protection of Beneficial Uses

Beneficial water uses which must be protected in providing for waste disposal are ordinarily listed in approximate order of priority. For any given area this order depends on legal decisions, local economic values, and the extent to which the beneficial uses might be damaged by a waste discharge. While disposal of treated sewage by dilution in tidal waters is itself a beneficial use of these waters, it is no longer regarded as a use to be protected to the detriment of other uses. Nevertheless, waste disposal is not necessarily incompatible with other uses. The beneficial uses described below are those uses of the bay and ocean adjacent to San Francisco that the Water Quality Control Board has declared its intention to protect, either as a matter of present policy or as a goal of future policy.

Industrial Water Supply. The waters of San Francisco Bay which are subject to quality impairment as a result of San Francisco waste discharges are used extensively for industrial purposes. For many industries, particularly along the eastern shoreline, the bay serves as the principal source of industrial cooling water.

Recreational Use. Unquestionably, the waters of the Pacific Ocean and of San Francisco Bay adjacent to San Francisco constitute one of the city's most valuable recreational assets. The extent of recreational use was defined in a report to the Regional Water Quality Control Board, prepared by the Board's staff and dated October 30, 1968, which states in part, "Almost all of the City and County's 30 miles of waterfront are used for recreation and esthetic enjoyment. There are 5.5 miles of continuous beach along the ocean and other beaches at Lincoln Park, the Presidio and Marina and Aquatic Parks. There are five marinas in the city. They are located at Marina Park, in the China Basin channel, and and adjacent to Mission Rock. There are also two boat launching ramps near Mission Rock. Fishermen use almost all of the shoreline from which they are not physically excluded. They are excluded from only a few piers and two shipyards. Even then the servicemen and employees fish at Hunters Point. They also fish from boats at several locations along the city's bay shore."

To preserve waters for recreational use, waste disposal must be accomplished without impairment of physical appearance, production of odors, or creation of a public health hazard. Of these, physical appearance relates to turbidity and discoloration, the presence of unsightly solids, or the presence of an oil or grease film on the water surface. Odor production usually results from the discharge of a waste which exceeds the dilution capacity of the receiving water. Bacterial contamination, of course, may be present in the absence of any visual evidence of sewage and thus may well be the greatest hazard.

Fishing and Fish Propagation. Throughout every season of the year the waters of the Pacific Ocean and of the bay adjacent to San Francisco serve either as a habitat or as a migration route for literally millions of striped bass, king and silver salmon, steelheads, and other sport fish. The shallow areas of San Francisco Bay and its estuaries are a natural habitat for shellfish, and the bay at one time supported a thriving commercial oyster industry. Over the years, however, sewage discharges have contaminated the growing areas to the point where shellfish within San Francisco Bay are no longer recognized as safe for human consumption.

For over 50 years the Gulf of the Farallones has been a bountiful source of Dungeness crab, a delicacy for which the restuarants of San Francisco are justly famous. From an all-time record of nearly 9 million pounds in the 1956-57 season, however, the crab catch has declined to a million pounds or less in recent years. While the reason for the decline has never been determined, many observers have postulated that water pollution must bear at least a portion of the blame.

Effective fish propagation requires a water environment not only in which fish will survive, but also in which there is an abundance of food material in the form of smaller fish, crustacea, and plankton. The primary criterion for survival of the most popular game fish, such as steelhead and salmon, is that the dissolved oxygen content of the water be maintained continuously in excess of 5 mg/l (milligrams per liter). So long as adequate oxygen resources are maintained, the discharge of sewage to a marine environment can, within limits, favor fish propagation by reason of the nutrients made available to the food chain organisms.

The recognition and protection of shellfishing as a beneficial use places more stringent requirements on waste disposal to a marine environment than does any other presently recognized beneficial use. The restrictive bacteriological requirements for waters to be protected for shellfishing place this beneficial use in most cases beyond the scope of present water quality objectives for San Francisco Bay. Nevertheless, it may be expected that as present objectives are attained attention will be turned to the protection of shellfishing in certain appropriate areas.

Other Beneficial Uses. Other beneficial uses listed for the receiving waters adjacent to the City and County of San Francisco include waterfowl habitat, navigation, and esthetic appeal. In general, the nature of these uses is such that they will be protected if the beneficial uses previously described are protected.

Dry Weather Requirements for Central Bay

The Regional Water Quality Control Board has established discharge requirements for all of the present waste discharges to the Central Bay. From time to time these requirements have been revised as water quality in the bay has improved and policy objectives have changed. Discharge requirements for the dry weather effluent from the North Point plant are set forth in Resolution No. 70-17, adopted March 26, 1970. Dry weather discharge requirements for the Southeast plant are contained in Resolution No. 69-44, adopted September 25, 1969. Similar requirements have been adopted for the dry weather discharge from the East Bay Municipal Utility District plant in Oakland. All of the above requirements are similar in content. They set specific quality limits on both the treated waste discharge (effluent requirements) and on the receiving waters affected by the discharge (receiving water requirements). The latter carry the greatest weight. In some cases certain effluent quality limitations may be exceeded so long as corresponding receiving water quality requirements are met. The most important points in the requirements, as they pertain both to the plant effluent and the receiving waters, are summarized below:

1. Plant effluent

a. Shall show substantially complete removal of settleable matter. The maximum allowable is set at an average value of 0.5 ml/l/hr (milliliters per liter per hour).

b. Shall be diluted at any point near the surface of the receiving water to 10 percent or less of the 96-hr TLm. The symbol TLm is used to denote median tolerance limit, which is a measure of toxic effects on test organisms under laboratory conditions. Median tolerance limit is defined as the waste concentration, expressed as a percentage, at which half of the test organisms die in the stated time.

2. Receiving water

a. Shall be free of floating, suspended, or deposited matter and objectionable aquatic growth caused by the waste discharge in quantity sufficient to affect the beneficial uses.

b. Shall not, because of the waste discharge, be appreciably altered in temperature, turbidity, or apparent color.

c. Shall have a minimum dissolved oxygen content of 5.0 mg/l at any point within one foot of the surface.

d. Shall have a pH between 7.0 and 8.5 at any point within one foot of the surface.

e. Shall not exceed a coliform organism count of 240 MPN/100 ml, as the median of five or more samples taken within one foot of the surface. If this requirement is not met in the receiving water, it must be met in the plant effluent.

3. Notification of additional requirements

The Board announces its intention, as soon as possible, to establish numerical requirements for transparency, grease, floatables, and nutrient concentrations in the receiving waters.

A summary of compliance with the above requirements, published by the Regional Water Quality Control Board and covering a period from September 1969 through January 1970, showed the North Point plant to be in significant violation of only two requirements. Floating material was found in the vicinity of the North Point discharge on 18 of 35 observations, and the waste discharge was judged to be discoloring the receiving waters on all 35 observations.

Wet Weather Requirements for Central Bay

By Resolution Nos. 70-2 and 70-3, adopted in January 1970, the Regional Board set requirements for all wet weather overflows from the city's combined sewerage system to the Central Bay. These requirements are for all practicable purposes the same as those for the discharge of effluent from the treatment plants, with two exceptions. The first is settleable matter, for which no requirement is set. The second is the toxicity requirement, which specifies at least a 75 percent survival of test fishes in the undiluted waste. This is more restrictive than the requirement for the dry weather effluent from treatment plants.

The requirements also specify the intention of the Board to set numerical limits on grease, settleable matter, floatables, and nutrients at the earlist practicable date. The Board's goals for settleable matter and grease are stated as 1.0 ml/l/hr and 25 mg/l respectively.

The present requirements for storm water overflows cannot be met without treatment at least equivalent to disinfection by chlorine, and the stated goals cannot be met without substantial additional treatment. Since all of the city's storm overflows are at present untreated, each discharge is in violation of requirements.

Disposal Requirements for Pacific Ocean

The attention of the Regional Water Quality Control Board has recently been focused on conditions within San Francisco Bay, while requirements established for disposal of wastes to the Pacific Ocean have remained unchanged for some time. Two sets of requirements are of particular interest to this study. The first prescribes requirements for the discharge from North San Mateo County Sanitation District's treatment plant through a submarine outfall sewer into the Pacific Ocean just north of the San Francisco south county line (Fig. 2-1). The second set covers the discharge of the Richmond-Sunset plant to the rocky shoreline at the base of the cliffs near Lands End.

Discharge requirements for the North San Mateo County Sanitation District were established in 1963. The only requirement placed on the plant effluent is for substantially complete removal of settleable matter, with the maximum allowable set at an average value of 0.5 ml/l/hr. For the receiving water, the requirements state:

1. No floating, suspended, or deposited material of waste origin shall be visible from shore.
2. No turbidity or discoloration shall occur more than 100 ft from the outfall diffuser.
3. Dissolved oxygen shall not fall below 5.0 mg/l.
4. The discharge shall not be toxic to aquatic life.
5. Waters along the shoreline shall comply with Title 17 of the Public Health Code for salt water bathing.

Requirements for the Richmond-Sunset plant, contained in Resolution No. 67-2, adopted in January 1967, are generally comparable to those for North San Mateo County Sanitary District. In recognition of the greater volume of the Richmond-Sunset discharge, and its near-shore location, the requirements presently allow a somewhat greater area for dispersion of the effluent. Within that dispersion area, which varies in size for different water quality parameters, certain allowable limits of the parameters may be exceeded. For example, turbidity and discoloration are permitted within 200 ft of the Mile Rock outfall, and dissolved oxygen may be below the required lower limit within 100 ft of the outfall. To date no separate requirements have been adopted to govern wet weather discharges to ocean waters.

Over the 9-month period from December 1969 to September 1970 the Regional Board recorded 22 violations of discharge requirements out of 60 separate observations. It is significant to note, however, that no violations were recorded in the last three months of that period. Aside from violations related to wet weather discharges, failure to meet requirements was confined principally to the areas of particulate matter on the beaches and unsatisfactory bacterial counts in the ocean waters.

Regional Board Policy Objectives

In addition to its regulatory powers, each regional water quality control board is charged with the responsibility for formulating and adopting long-range plans and policy for water quality control within its region. The San Francisco Bay Regional Board adopted two major policy statements in 1967, one pertaining to waste discharges within the San Francisco Bay drainage and the other for waste discharges to the Pacific Ocean.

Regional Board Bay Policy. Resolution No. 67-30, adopted by the Regional Water Quality Control Board in June 1967, established water quality control policy for tidal waters inland from the Golden Gate within the San Francisco Bay region. Since the resolution lists policy objectives, it is not specific regarding numerical values or methods of enforcement. These factors are taken into account in the adoption of discharge requirements. Those portions of the water quality control policy which are of special significance in the planning of waste disposal for the Central Bay are summarized below:

1. Temperature, turbidity and apparent color shall exhibit no significant variation beyond natural background levels.
2. No floating materials, bottom deposits or odors other than of natural causes shall be present at any place.
3. No suspended or deposited oil or materials of petroleum origin shall be present at any place, and floating oil shall not be present in sufficient quantity to cause irridescence on the water surface.
4. Dissolved oxygen concentration shall not be less than 5 mg/l.
5. Toxic or deleterious substances shall not be present in concentrations which adversely affect any beneficial use or which render aquatic life or wildlife unfit for human consumption.
6. The bacteriological quality objective for bay waters is an MPN of 1000 per 100 ml in 80 percent or more of the samples tested at any point where the water is accessible to the public and suitable for water-contact recreation. This policy objective will be applicable to virtually the entire waterfront of the City of San Francisco.
7. Nutrients from waste sources shall not cause abnormal biotic growths.
8. Certain areas of the bay may be protected for the taking of shellfish, and these areas must meet the bacteriological requirements for shellfishing for human consumption.
9. Waste dispersion and assimilation is recognized as a use which will be permitted to the extent that it does not objectionably or unreasonably interfere with beneficial uses to be protected.
10. The Water Quality Control Board considers that dilution areas are not fixed and are subject to constant review, with the ultimate objective of their complete elimination or substantial reduction in size.
11. The Board encourages dischargers to investigate the advantages of deepwater outfalls.

Regional Board Ocean Policy. Quality objectives for ocean waters are set forth in Resolution No. 67-25, adopted in May 1967, which established water quality control policy for the Pacific Ocean from Pescadero Point to the mouth of Tomales Bay. The ocean area covered by this policy statement includes the entire Gulf of the Farallones from the Golden Gate westward to the Farallon Islands and from Point Montara on the south to Point Reyes on the north. Quality objectives vary depending on whether the area under consideration is nearshore or offshore, whether the bottom is sandy or rocky, and whether kelp beds are present or absent. Nearshore waters are defined as those ocean waters extending 1,000 ft seaward of the shoreline at two feet below mean lower low water. The distance may be extended further offshore to encompass water contact recreational areas. Offshore waters are all ocean waters seaward of nearshore waters.

In general, water quality objectives are less stringent in areas where the bottom is sandy and where kelp beds are absent. Objectives are also less stringent for offshore waters than for nearshore waters. The ocean areas considered in this report for disposal of San Francisco's sewage effluent all have sandy bottoms without kelp beds. Keeping these facts in mind, the policy statements by the Regional Board which will strongly influence plans for ocean disposal of liquid wastes by the City of San Francisco are summarized below:

1. No policy objective has been established for bacteriological quality of offshore waters.

2. The bacteriological quality objective for nearshore waters is an MPN of 1000 per 100 ml or less in 80 percent of the samples, except that in areas protected for the taking of shellfish the median MPN for samples collected at the beach is 70 per 100 ml.

3. Dissolved oxygen shall be maintained at a mean annual level of 6.0 mg/l, and no single sample shall be less than 5.0 mg/l except where natural factors cause lesser concentrations.

4. No waste discharge shall cause a significant variation in temperature, salinity, turbidity, or apparent color beyond present natural background levels.

5. There shall be no bottom deposits, odors, or floating material from other than natural causes.

6. No suspended or deposited oil or material of petroleum origin shall be present at any place. For offshore waters, floating oil shall not be present in "objectionable amounts." For nearshore waters, floating oil shall not be sufficient to cause irridescence.

7. Toxic or deleterious substances shall not be present in concentrations which adversely affect any beneficial use or which render aquatic life or wildlife unfit for human consumption.

8. Nutrients from waste sources shall not cause deleterious or abnormal biotic growths.

Insofar as the discharge of domestic sewage effluents is concerned, the only significant difference between discharge to nearshore and offshore waters is the fact that the present policy sets no objective for coliform organisms in the offshore waters. This does not, of course, preclude the establishment of coliform requirements for a specific discharge.

Bay-Delta Program Policy Objectives

Policy planning within the San Francisco Bay region and adjacent waters is influenced by the findings and recommendations of the Bay-Delta Program. This influence is evident in the discharge requirements adopted by the Regional Board since the Bay-Delta report was published.

As stated in the Kaiser Engineers' report, there are no significant differences in the objectives of Bay-Delta policy and Regional Board policy. The principal differences result from the attempt by Bay-Delta to interpret as many objectives as possible in quantitative terms which could be applied to the design of a water quality control program. As with the Regional Board, the Bay-Delta Program established separate policy objectives for the bay and ocean. Those Bay-Delta policy objectives which are different from, more stringent, or more specific than the policy statements of the Regional Board are presented below:

Bay-Delta Objectives for San Francisco Bay

1. The objective for dissolved oxygen is a median value of 7.0 mg/l and a 95 percentile value of 6.0 mg/l. This objective is more stringent than the Regional Board objective, which simply specifies a minimum value of 5.0 mg/l.

2. The objective for coliform organisms is a median MPN of 70/100 ml. This objective would apply to the entire bay, whereas the objectives of the Regional Board would require a median of 70/100 ml only in areas to be specifically designated for the taking of shellfish.

3. To reduce toxicity, a minimum dilution of 25 to 1 is recommended for all wastes at any point.

4. Floatable materials and oily substances are lumped together, and a maximum surface concentration of 20 mg/sq m (milligrams per square meter) is recommended for the receiving waters. Recommended maximum concentration on shore areas is 300 mg/sq m.

Bay-Delta Objectives for Pacific Ocean. Whereas the Regional Board expressed its ocean policy only in terms of the receiving waters, the Bay-Delta Program sets objectives for the waste stream, the initial mixing zone, and the nearshore waters. Bay-Delta defines nearshore waters as extending one mile offshore, as opposed to the definition of 1,000 ft offshore used in Regional Board policy.

1. The waste stream shall have:
   a. Suspended solids removal of 55 percent.
   b. Floatables removal of 60 percent.
   c. Initial dilution of at least 80 to 1, with a median of 100 to 1.

2. The initial mixing zone shall have:
   a. Dissolved oxygen level at least 80 percent of background.
   b. Temperature within 2 deg F. (degrees Fahrenheit) of background.
   c. A maximum 50 percent decrease in light transmittance at a depth of 25 meters and a maximum 20 percent decrease in waters less than 25 meters in depth.

3. The nearshore waters shall have an MPN of 1000 per 100 ml or less in 80 percent of the samples collected within one mile of shore, and a median MPN of 70 per 100 ml in all samples collected in the surf zone.

Federal Water Quality Control Policy

The policy of the federal government toward water quality control was in a state of flux at the time this report was written. There is every indication that the federal government intends to take an active role in enforcement as a response to political pressure being brought to bear by the environmentalists. One of the principal means of enforcement will be the withholding of federal grants for non-compliance with federal water quality objectives. As this report was written, however, indications were that the Corps of Engineers, through its power to grant construction permits and regulate dumping into navigable waterways, will play an increasingly important part in enforcement of federal objectives.

The most recently proposed minimum requirements which must be met in order to qualify for a federal construction grant were published in the Federal Register on June 10, 1970. They set four conditions on grant eligibility for treatment and disposal works, summarized as follows:

1. The plant must remove substantially all floatable and settleable material.
2. The plant must remove 85 percent of the 5-day BOD, except that the Commissioner may waive this requirement if the project discharges into open ocean waters through an ocean outfall in a manner which will not adversely affect the open ocean environment and adjoining shores.
3. Removal of micro-organisms by disinfection must be substantially complete.
4. Additional treatment must be applied as necessary to meet applicable water quality standards. In this case, "applicable water quality standards" are the discharge requirements of the Regional Water Quality Control Board.

DEEP WATER DISPOSAL

The capacity of the marine environment to accept sewage effluent and render it harmless depends on its ability to dilute, disperse, degrade, or otherwise reduce the concentration of sewage-borne organisms and toxic elements, and to oxidize and thereby stabilize the entering organic matter. The extent to which these functions can be performed depends on the quantity and composition of the sewage, the current and dispersion chararteristics of the receiving water, and the manner in which the waste is introduced into the receiving waters.

Before considering the suitability of specific deep water disposal points, it is well to review the mechanisms which control water quality when a waste is discharged through a submarine outfall sewer. These are four in number: (1) the initial dilution which takes place as the sewage rises to the surface, (2) subsequent dilution after the sewage reaches the surface, (3) the disappearance or reduction of coliform organisms, and (4) the behaviour of local currents. Initial dilution and the disappearance of coliform organisms have been well defined through research and field investigation. The technical literature on these two factors provides a valid basis for design. Dilution of the surface effluent field and the effect of local currents can be analyzed using data collected from oceanographic investigations.

Initial Dilution

When sewage effluent is discharged into sea water, it is immediately subjected to a buoyant force proportional to the difference in density between the sewage and the surrounding salt water. This force bends a horizontal discharge towards the surface and accelerates its ascent. Because of the relative motion between the discharged sewage jet and the sea water, turbulence is generated and mixing takes place. Experimental data and relationships describing this phase of initial dilution were developed by Rawn and Palmer and expanded by Rawn, Bowerman and Brooks.[7]

Where the surface waters are less saline or higher in temperature than at the bottom, a density gradient will exist. When the sewage jet is discharged into the denser bottom water, the resulting sewage-sea water mixture often achieves a density slightly greater than that of the surface layer. In such cases, the mixture will either remain below the surface of the receiving body and continue to spread and disperse, or will be carried to the surface by the kinetic energy residing in the rising mixture, subsequently to sink below the surface and remain submerged. The dilution required to bring about submergence or resubmergence can be calculated once the temperature and salinity characteristics of the receiving waters are known. If field submergence does not occur, the sewage-sea water mixture will rise to the surface and spread out as a part of the surface layer.

An understanding of the basic mechanisms of initial dilution as set forth by Rawn, et al, led to the development of long submerged diffusers with a large number of small diameter ports for discharge of treated sewage effluents. Where conditions are suitable it is usually possible with a properly designed diffuser to achieve initial dilutions in excess of 100 to 1. The factors which affect the degree of initial dilution are the water depth, the size and spacing of diffuser ports, the hydraulic head available to create an initial jet velocity, and the physical characteristics of the water mass overlying the diffuser. Once the physical characteristics of the receiving water have been determined, the designed can vary all of the other factors to arrive at an optimum design. Depth of discharge, for example, is frequently influenced by economic considerations associated with a proposed outfall site. In some cases many miles of pipeline are required to reach a discharge depth of 150 to 200 ft. In some circumstances, however, long diffusers placed in shallow water will produce initial dilutions comparable to shorter diffusers to deep water.

The calculation of diffuser performance and initial dilution is a long and tedious mathematical process which makes an ideal application for computer analysis. Ditmars[8] in 1969 developed a computer program based on recent work by Dr. Norman H. Brooks of California Institute of Technology which analyzes initial dilution of a single round jet of sewage effluent discharged into sea water. In the usual case, a number of jets discharging side by side soon merge to form a single buoyant jet which has the same characteristics as a single jet discharged from a continuous slot in the pipe wall. Equations to predict the performance of slot jets were developed by Brooks, Koh and Fan.[9,10] Brown and Caldwell incorporated the slot jet equations into the single jet program by Ditmars to permit analysis of the case where single jets merge to form a line source. As the effluent field rises and becomes more dilute its density is progressively computed and compared to the density of the sea water above. When the density of the field becomes equal to or greater than the surrounding sea water, the point and dilution at which the field will cease to rise is computed. Because of the momentum in the rising effluent plume, the submerged field will actually stabilize at a level slightly above the point of equilibrium, and this factor is included in the analysis.

The computer analysis considers dilution in turbulent jets due to momentum, buoyancy and stratification effects, but does not consider the effect of currents in the receiving waters. However, subsurface currents and turbulence will cause greater than predicted mixing and dilution. This effect is evident in Fig. 3-1, which shows views of a model diffuser port discharging with an imposed current. Prototype conditions represented in the model were a current speed of 0.62 fps (feet per second) and a jet discharge and velocity of 2.0 cfs (cubic feet per second) and 16 fps respectively. The upper picture shows a jet discharging against or in opposition to the imposed current. The lower picture shows a jet discharging in the same direction as the current. Turbulence caused by the water passing the diffuser pipe has a marked effect on the amount of dilution taking place after discharge. While there is no satisfactory mathematical basis for calculating the effect of current on a buoyant jet, we know that dilution is increased. For strong currents, dilution may be increased by a factor of 2 or 3, or even more.

The ability of the computer program to predict diffuser performance accurately was verified in the course of an evaluation of the existing Southeast plant diffuser, which was conducted in April 1970 and is described in Chapter 4. The computer program predicted a minimum initial dilution of 40 to 1 at the surface. Minimum dilution as measured in the field by continuous dye release was 53 to 1, occurring as expected at slack water. Minimum dilution measured during maximum flood, in an area where flood currents average about 1.6 knots, was 140 to 1.

Subsequent Dilution

After reaching equilibrium with its surroundings, whether submerged or in the surface layer, the sewage-sea water mixture is subject to further mixing action which is defined as subsequent dilution. Subsequent dilution takes place by turbulent diffusion in the sea water mass as it is convected away from the outfall site. Except in unusual cases where strong vertical currents or turbulence exist, diffusion is much greater in the horizontal direction than in the vertical direction. Hence, the area of a field of diluting effluent increases much faster than its thickness. Compared with the very rapid initial mixing attained by the turbulent jet action, which may yeild initial dilutions of 100 to 1 in a minute or two, subsequent mixing to attain a further dilution of 10 to 1 may take several hours.

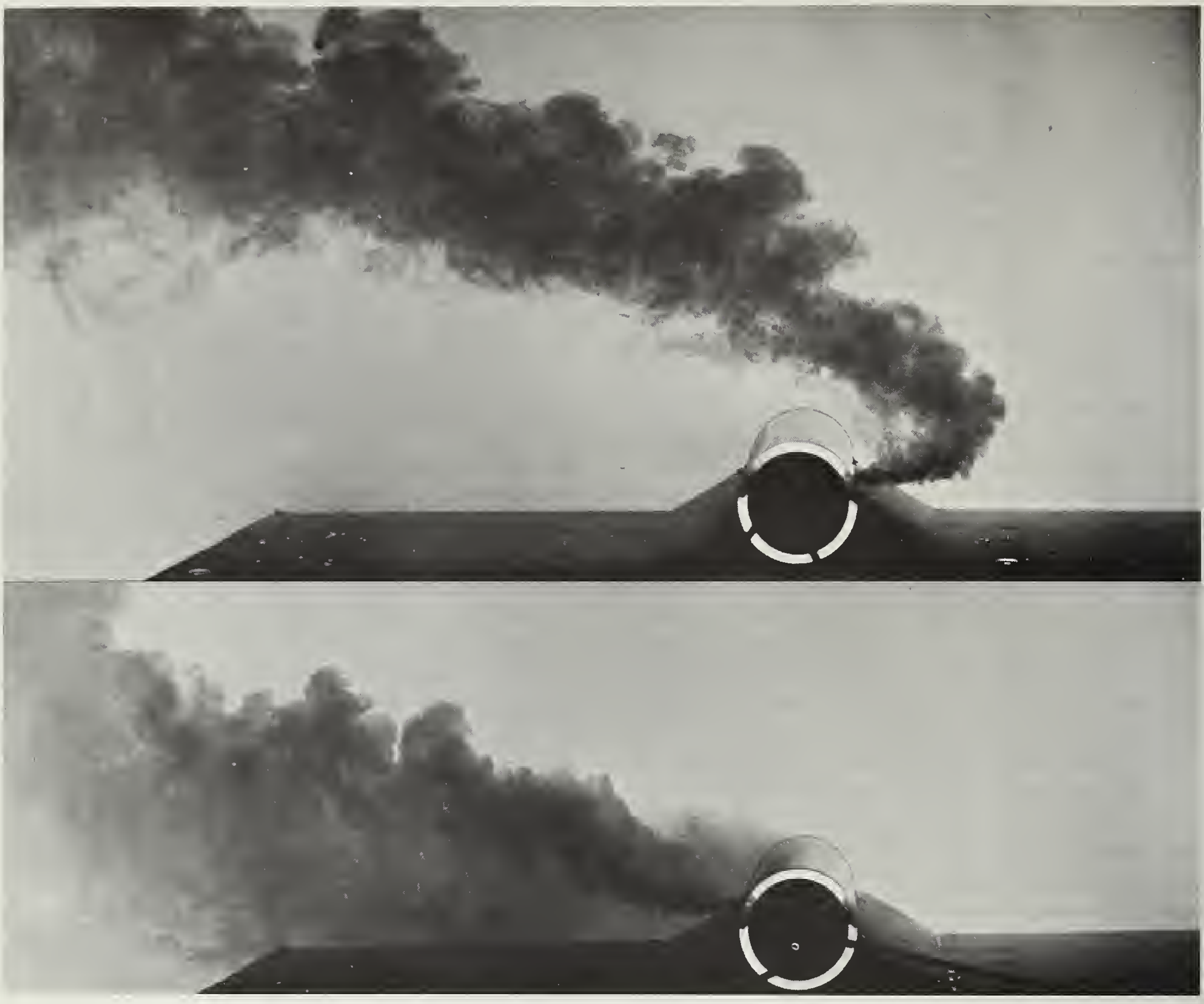


Fig. 3-1 Effect of Current on Initial Dilution of a Buoyant Jet

Brooks[15] has provided solutions to the problem of subsequent dilution for the case of the dispersion coefficient varying with scale by the "four thirds law":

$$k = \alpha (L)^{4/3} \tag{1}$$

where k = turbulent diffusion or dispersion coefficient, sq ft/hr,

α = four-thirds law coefficient, and

L = scale or width of the sewage field, ft.

Equation (1) has gained wide acceptance and has been used by Pearson[14] to correlate dispersion data from a number of different observations in coastal waters. Pearson obtained a value for α of 3.6 $\mathrm{ft}^{2/3}/\mathrm{hr}$, but values reported for different areas have been known to vary by several orders of magnitude. Considering the wide variety of ocean conditions under which the observations were conducted, such variation is understandable.

Brooks' equations for subsequent dilution and spreading of the sewage field are:

$$C = C_o \operatorname{erf} \sqrt{\frac{3/2}{\left[1 + \frac{2\beta X}{3b}\right]^3 - 1}} \tag{2}$$

, and

$$L = b\left[1 + \frac{8\,\alpha X}{b^{2/3}U}\right]^{3/2} \quad \textbf{(3)}$$
,

where $C_o =$ the concentration at the surface after initial dilution,
$C =$ concentration at distance X,
$X =$ distance traveled from line source,
$b =$ diffuser length,
$U =$ current velocity,
$L =$ width of the sewage field $= 2\sqrt{3}\,\sigma$
$\beta = 12\alpha\,(b)^{1/3}$,
$\sigma =$ standard deviation, and
$\mathrm{erf} =$ error function.

Equations 2 and 3 can be used in the design of marine outfalls to define the dilution and range of influence of a sewage field as a function of the distance away from the outfall.

Analysis of field diffusion data may yield diffusion scale relationships with exponent values other than 4/3, of the form

$$k = \alpha\,(L)^m$$

The general solutions for scale and dilution for 1<m>2 are:

$$C = C_o e^{-kt} \mathrm{erf}\sqrt{\frac{3/2}{\left[1 + \frac{12(2-m)\,\alpha X}{Ub^{2-m}}\right]^{2/(2-m)} - 1}} \quad \textbf{(4)}$$

, and

$$L = b\left[1 + \frac{12(2-m)\,\alpha X}{Ub^{2-m}}\right]^{1/(2-m)} \quad \textbf{(5)}$$

A computer program was developed for solution of equations 2 through 5 to permit the easy application of data derived from field observations to the analysis of waste disposal alternatives.

Reduction of Coliform Organisms

Although dilution is the primary factor in reducing coliform organism concentrations in sewage discharged from a diffuser, coliforms are also diminished by (1) bactericidal action of the sea water, (2) consumption by protozoans and other small animals, (3) sedimentation and adsorption in the receiving water and (4) normal biological mortality or die-off.[11]

Any test designed to measure true bacterial concentrations subsequent to discharge into a receiving water must therefore measure a combination of dilution and disappearance. For this reason it is difficult to devise a means of comparison between observed oceanographic conditions and measured bacterial concentrations. Where adequate oceanographic data are available, a satisfactory answer can be obtained for subsequent dilution. In addition, to arrive at an answer for the rate of total coliform reduction per unit of time, the effect of the above four items must be estimated as a whole.

As employed herein, the rate of coliform bacteria disappearance, T-90, is defined as the time required for a 90 percent reduction in coliform concentration due to the combined effect of all factors except physical dilution. Normally, the disappearance rate is assumed to be constant for any given body of water. Hyperion Engineers, in a 1957 report to the City of Los Angeles,[12] quoted a number of references in which T-90 for bacterial decline exclusive of the effects of physical dilution varied from 2 to 4.8 hours under actual field conditions. The San Francisco Bay-Delta Water Quality Control Program adopted a value of 4 hours for T-90 in its study of submarine outfalls off the coast of San Mateo County,[13] and the same value appears to be appropriate for the purposes of this study. The curve shown on Fig. 3-2, prepared using a formula developed by Brooks, represents the apparent dilution due to bacterial decline for a T-90 value of 4 hours.

The same procedure can be employed to predict the change in concentration of any nonconservative waste constituent, provided that the decay rate is known. For this study, however, coliforms were the only factor which warranted such an analysis.

Settleable and Floatable Material

The mechanisms of initial dilution, subsequent dilution, and decay can be used to calculate concentrations of any suspended or dissolved constituent at any point once the oceanographic characteristics of the area are known. The same techniques of analysis are not applicable to settleable and floatable materials, because these materials tend to reconcentrate on the bottom or surface. The rate at which reconcentration occurs will depend on the size and specific gravity of the particles.

An accumulation of solids of waste origin is generally regarded as harmful to benthic (bottom-

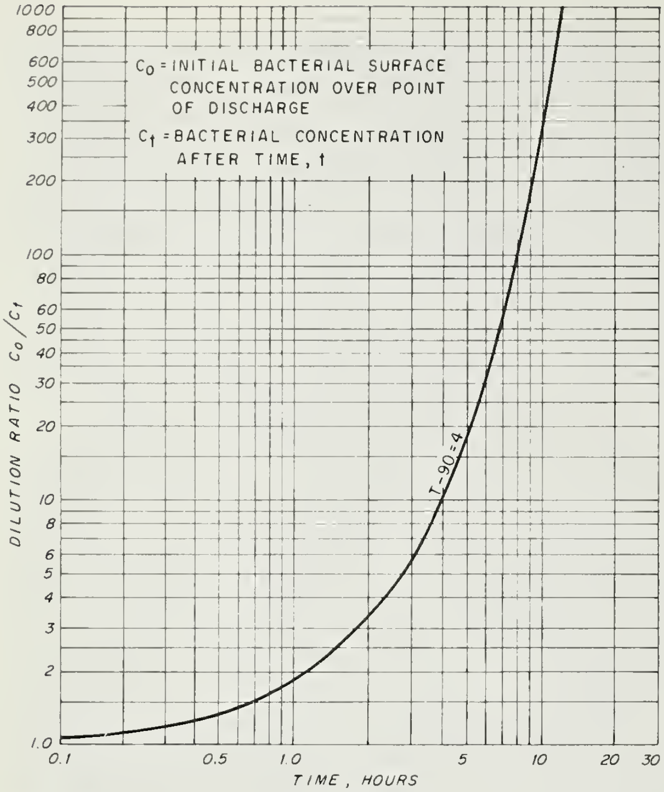


Fig. 3-2 **Apparent Dilution Ratio Due to Decline of Sewage Bacteria**

dwelling) organisms, and changes in bethnic populations are frequently used as an indicator of pollution. For solids to accumulate at the bottom the particles must be heavy enough to settle, and the water must be quiescent enough to permit the particles to remain on the bottom without resuspension. It is intesting to note that the weight of the largest particle of sediment that can be transported by flowing water increases as the sixth power of the velocity. Thus, a current of 2 knots will transport particles 4,000 times as heavy as a current of 0.5 knots, and 256,000 times as heavy as a current of 0.25 knots. Bottom sediments are continuously sorted by currents, and inspection of the sediment particle size in a given area will provide a good indication of the minimum size of particles which will be deposited and remain in that area.

Settleable material will eventually come to rest on the bottom in quiet water. Floatable material, on the other hand, will rise to the surface and continue to move with the surface water film until it is deposited on the shore, degraded through chemical or biological action, or changed in physical makeup to a settleable solid. As stated in a 1970 joint report by the National Academy of Sciences and the National Academy of Engineering,[16] "Investigations of surface materials of municipal wastewater origin have been extremely scarce. The results of the very few actually conducted on floatables tend to indicate that they may be blown onto beaches in objectionable quantities. For example, it has been found that most harbors and many beaches in California are polluted with oils, with the source of the oil being ascribed to natural submarine oil seeps, accidental oil spills and industrial waste waters rather than municipal wastes." The same report further states, "Apparently, slight quantities of floatables of wastewater origin may cause appreciable slick formation because (a) the materials are concentrated into a two-dimensional plane at the air-water interface and (b) they are concentrated still further into slicks and windrows by natural surface circulation phenomena."

If not removed by the treatment process, floatable material of typical domestic sewage origin may manifest itself as an esthetically displeasing slick on the water surface or as a deposit of scum and particulate matter along the shoreline. The rate at which floatables are biologically degraded or otherwise destroyed is poorly understood at present, but it is believed to involve a number of mechanisms, including evaporation, chemical or biological oxidation, adsorption and sedimentation. Based on limited information, the Bay-Delta Program[2] assumed that the rate of removal of floatables from both the water surface and the shore is 3.5 percent per day.

As floatable material moves with the water mass it is subject to further transport by the wind. Wind exerts a marked effect on particulate matter in the surface film, and may move floatable material rapidly downwind in a direction quite different from the direction of movement of the water mass.

CHAPTER 4

PHYSICAL OCEANOGRAPHY

An intelligent prediction of the impact of waste disposal on the marine environment can be made only after the physical and ecological make-up of the environment is understood. In addition to those physical factors which influence dilution of the sewage field, as described in Chapter 3, a study of this nature must be concerned with mass water movement, current direction and velocity, and the physical and chemical make-up of the water mass. Such factors as temperature, salinity, dissolved oxygen content, and water clarity all affect the marine environment independently of waste discharges.

Field work was confined to the water areas of particular concern to this study, specifically, the Central Bay and the Gulf of the Farallones adjacent to the Golden Gate. A discussion of physical oceanography can thus be presented in four phases. First is the general oceanography of the Central California coastal area, as defined in the literature. The second phase is the oceanography of the Gulf of the Farallones as developed from the field work conducted in the course of this study. The third phase describes the physical oceanography of the Central Bay as defined by this study and by previous observers. The fourth phase relates to specific aspects of oceanography which are concerned with the transition from bay to ocean, particularly the phenomenon of tidal exchange.

PHYSICAL OCEANOGRAPHY OF CENTRAL CALIFORNIA COAST

The major oceanographic features of the Pacific Ocean west of the coast of Central California have been investigated by a number of observers and reported in the technical literature. Two principal references on the subject are the reports published by California Cooperative Oceanic Fisheries Investigations (commonly called CalCOFI) and the final report on special oceanic studies for the Bay-Delta Program.[4] The CalCOFI reports, which present periodic summaries of oceanographic work conducted on a continuing basis since 1956, contain much of the basic data on the area. The Special Oceanographic Studies for the Bay-Delta Program present a summary of the CalCOFI work as well as other investigations and report the information which is specifically related to the Central California coastal area.

The Pacific Ocean off the coast of Central California has two basic oceanographic seasons, which are (1) the Dry Season when the southerly California Current is the prevailing nearshore current; and (2) the Rainy Season when the northerly Davidson Current interposes itself between the coast and the California Current. The Dry Season current regime further may be divided into two periods: (a) the period of upwelling during the Fog Season of late spring and summer; and (b) the period of no upwelling during the clear hot weather of the late summer-fall, or the so-called Oceanic period. A schematic diagram of prevailing currents along the Central California coast is shown in Fig. 4-1, taken from UCB Hydraulic Engineering Laboratory Report No HEL 2-13.[27]

California Current Season

As described in a CalCOFI progress report,[19] "The California Current system is a part of the great clockwise circulation of the North Pacific Ocean. At high latitudes the waters move eastward under the influence of the strong westerly winds (the 'roaring forties') and near the coast of North America divide into two branches. The smaller part turns northward into the Gulf of Alaska, and the larger part turns southward to become the California Current. The water which is brought south by the California Current system is cooler than the waters farther offshore. As the current slowly moves south at speeds generally less than half a knot it becomes warmer under the influence of the sun and by mixing with the warmer waters to the west. As it nears the latitude of 25 deg N it begins to turn westward and its waters become part of the west-flowing North Equatorial Current."

The California Current system as described above has been identified for a distance of about 300 miles offshore of the Central California coast. The basic pattern may be said to reflect moder-

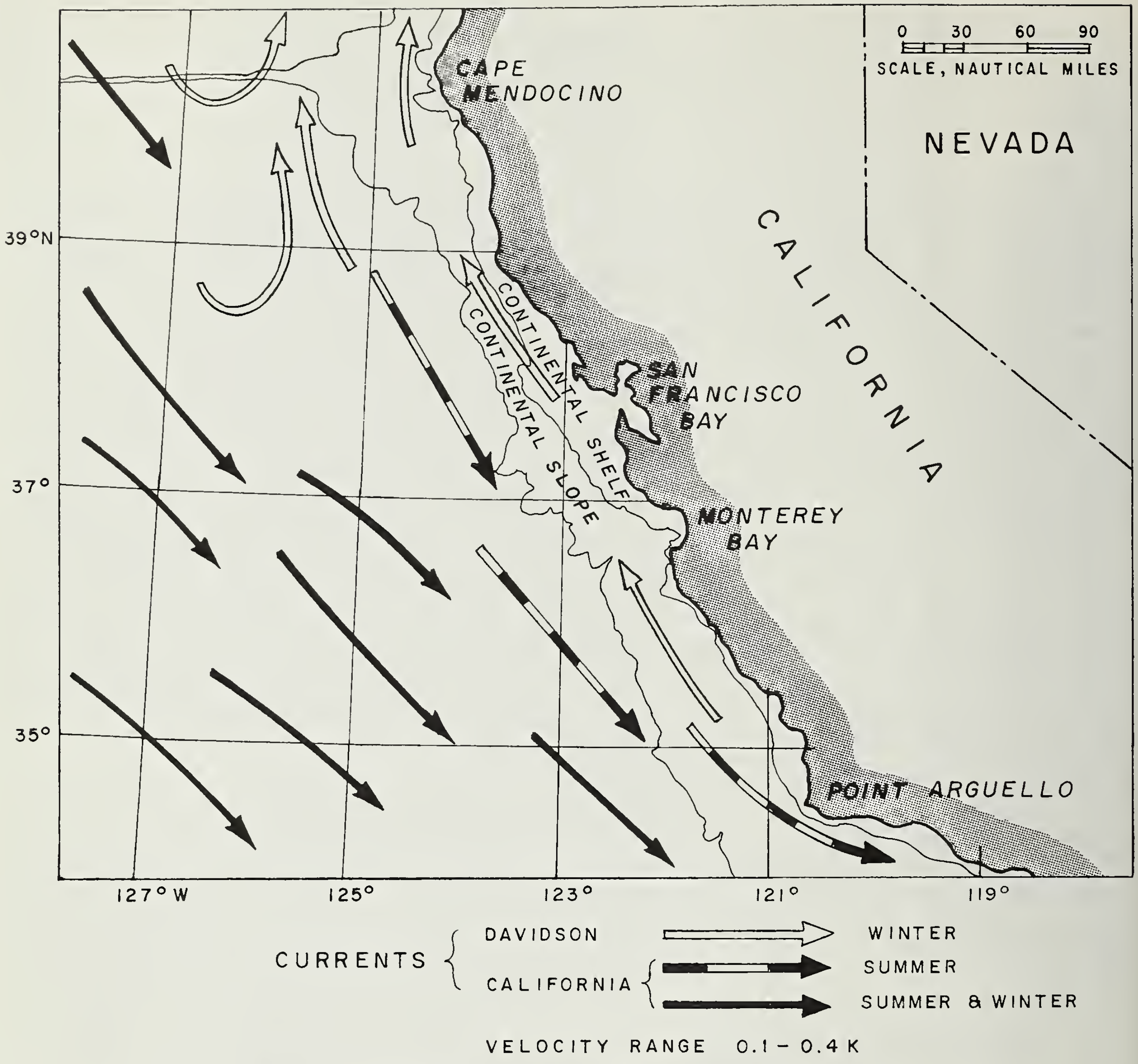


Fig. 4-1 Prevailing Currents of the Central California Coast

ately scaled features of the ocean; that is, features whose minimum size is on the order of tens of miles. Coastal currents very near shore do not necessarily conform to the features of the deep ocean current system. Such factors as coastline configuration and local upwelling may have an overriding effect on nearshore currents.

Upwelling Period. During the Fog Season, from April or the end of the Rainy Season to August, periodic welling of colder water from depth occurs along the California coast. At this time of year, a stationary high pressure system is likely to prevail offshore. Clockwise circulation around this high produces reasonably persistant north and northwest winds. Persistant winds in the Northern Hemisphere will produce surface water movement to the right of the wind. For the California situation the surface waters will move westward, or offshore. The westward moving surface waters are replaced by colder, nutrient-laden waters from depth which move upward to restore level. The depth from which the upwelling water is derived as well as the duration of the upwelling are func-

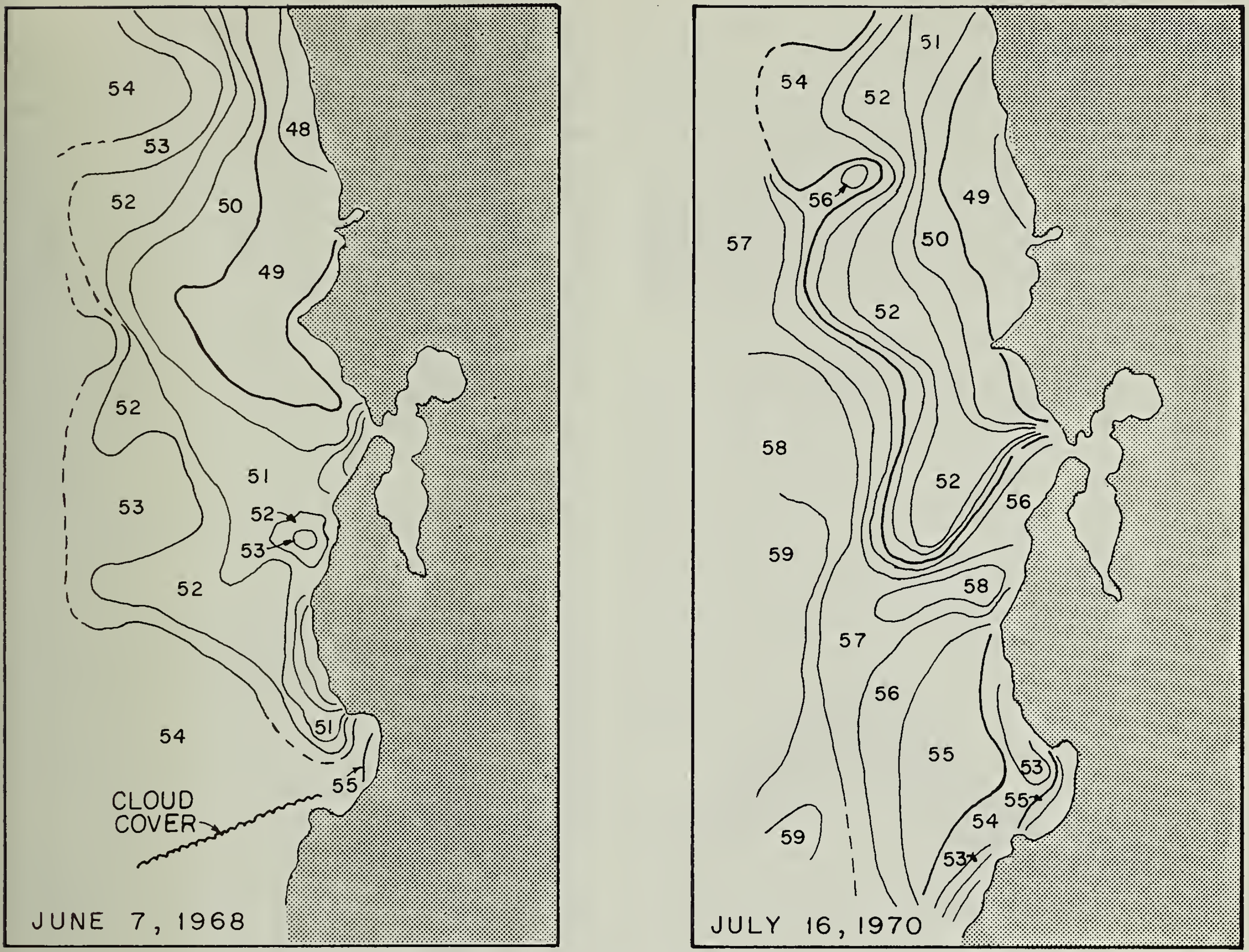


Fig. 4-2 **Ocean Surface Temperatures West of San Francisco Bay During Upwelling**

tions of the persistence of the winds blowing parallel to the coast, which maintain the offshore water movement. Weather systems are seldom stationary very long; thus, upwelling may not occur at all times during Fog Season. Such variations are seen in Fog Season as days or even weeks of clear weather (no upwelling) interspersed with the usual fog (upwelling). Typical ocean surface temperature patterns created by upwelling are shown in Fig. 4-2.

Oceanic Period. In the late summer and fall when the winds blowing from the north and northwest die down, upwelling and fog cease. At this time the California Current really moves on shore. The clear skies and lack of winds which generate smog also let the sun heat the surface waters of the bay and to a lesser degree the neighboring ocean. Also during this period at the end of the Dry Season there is no surface run-off from most coastal streams and very little run-off from the Central Valley coming into San Francisco Bay.

That portion of the California Current season between the cessation of upwelling and the start of the Davidson Current is identified by some oceanographers as the Oceanic period. As described in Special Oceanographic Studies for the Bay-Delta Program,[4] the characteristics of the Oceanic period are as follows:

1. Ocean surface temperatures are at the year's maximum.
2. The spread between the maximum and minimum surface temperatures is moderately large.

3. There is a persistent strong vertical temperature gradient.
4. Temperature values at all levels are 2 or 3 deg C. (degrees Centigrade) higher than during the peak of the previous upwelling period.
5. Surface salinities are rising slightly.

The change in surface temperature of the ocean west of San Francisco with the changing seasons is illustrated in Fig. 4-3, taken from a 1969 special publication of the Naval Oceanographic Office.[21]

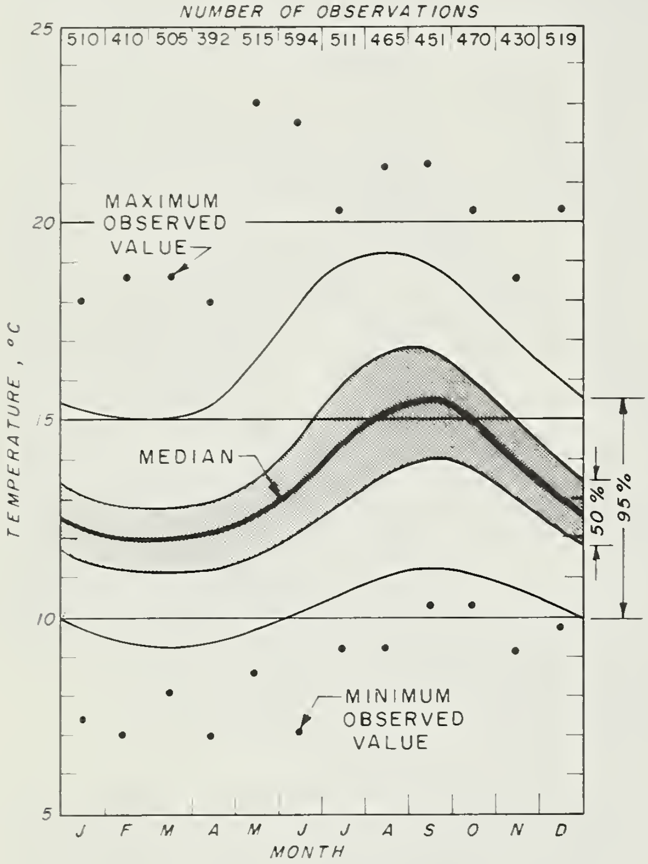


Fig. 4-3 Seasonal Change in Ocean Surface Temperature West of San Francisco

Davidson Current Season

During the Rainy Season from November to April, periodically a northward flowing current called the Davidson Current is found inshore of the California Current. At this time, in contrast to the Dry Season, low pressure systems are common offshore. Counter-clockwise circulation around low pressure will produce south and southwest winds along the Central California coast. Such winds will produce surface water movements again to the right of the wind, but in this case, on shore. These onshore currents are blocked by the northwest trending coast and gain a northerly set which generates the Davidson Current. Low pressure is even less likely than high pressure to remain stationary. Thus, the Davidson Current, like upwelling, does not occur all the time. However, stream run-off is a stabilizing factor which makes the Davidson Current persist much longer than would be predicted from the wind patterns. Fresh water discharged from streams into the ocean during the Rainy Season is lighter than ocean water. Water at the edge of the lighter fresher plume, on a western coast in the Northern Hemisphere, will move north due to the rotation of the Earth. Thus the combination of the prevailing wind patterns and stream run-off during the Rainy Season may produce a northward flowing coastal current.

As described in CalCOFI Reports, Volume IX,[20] the Davidson Current can be at least 50 miles wide with speeds of at least 0.5 to 0.9 knots for distances of several hundred miles. The important unique features of the countercurrent are its narrowness compared to its length and its ability to carry drift bottles at speeds over 0.5 knots for long distances before they come ashore.

An interesting example of the effect of the Davidson Current was described in the Berkeley Gazette on March 12, 1970. On that date a 33-ft trimaran, which was disabled and abandoned on the bar outside the Golden Gate 46 days earlier, was towed ashore by the Coast Guard at Coos Bay, Oregon. The abandoned craft had drifted 360 miles northward at an average speed of 0.33 knots.

Tides

Along the Central California coast tidal changes produce two high and two low waters during each lunar day of approximately 25 hours. One of the chief characteristics of the tides of this region is diurnal inequality, a difference in height of successive high or low waters. The amount of inequality varies from day to day, modulating from approximately equal tides to maximum inequality and back to equal tides twice in each lunar month of 28 days. Tidal range measured from higher high to lower low water seldom exceeds eight feet, and the mean range is only about four feet.[22]

DATA COLLECTION METHODS

Once the goals of the physical oceanographic program had been established, procedures were developed for collecting the information necessary to achieve the goals. Some of the data collection procedures were used throughout the study without modification, while in other cases initial experience indicated the need for modifications in methods and equipment. All procedures were evaluated at the end of each cruise and modified as necessary. Times referred to in the report are local time, either standard or daylight saving time depending on the season.

Boats

The first two cruises were conducted in February of 1970. On each of these cruises two boats were employed. The R/V Inland Seas, an 85-ft converted AVR out of Oyster Point, was used for 25-hr continuous monitoring of physical-chemical characteristics and for installation and retrieval of the in-situ current metering systems. A smaller charter boat, the 35-ft. Evie K out of Berkeley Yacht Harbor, was employed on the first cruise for daylight to dark work on dye dispersion rates and on measurement of changing physical-chemical characteristics of the moving water mass. Though fast, the Evie K lacked radar, which was found to be necessary for good position control. On the second cruise, therefore, the Fisherman's Grotto No. 9, a 50-ft charter boat out of Fisherman's Wharf, was used for the daylight to dark work.

After the two initial cruises an evaluation of methods showed that simultaneous work by two boats gave no major advantage in terms of usefulness of the data collected. For the summer and fall cruises, therefore, the work program was organized to conduct all of the work on successive days with a single boat. All oceanographic cruises from June on were conducted aboard the R/V Amigo, a 50-ft oceanographic research vessel out of Santa Cruz.

Mass Water Movement

The principal tool used in measuring mass water movement was aerial photography. Reconnaissance flights in a light plane during the fall of 1969 gave evidence that the movement of more turbid water out of San Francisco Bay and into the ocean could be tracked visually and photographically by recording the changing position of the advancing turbidity front. Significantly, the turbidity front was visible even during the fall months of maximum bay water clarity. Initial program planning included a high altitude photogrammetric flight, but without ground control, to be carried out at the time each surface cruise was in progress. The plan was to define the position of the water mass accurately with a single photogrammetric flight, then fill in the dynamics of mass movement with aerial obliques taken from a light plane before and after the high altitude flight.

After the two initial runs on this program it was concluded that more useful information could be obtained by taking only obliques from a light plane. The advantage of this arrangement lay in having a photographer who was an engineer familiar with the goals of the program and capable of making sketches and qualitative judgements on the observed phenomena. This arrangement also worked well in conjunction with the dye dispersion studies, for it was found on the first cruise that the dispersing dye patches were more visible from the air than from the surface. On all subsequent dye studies, therefore, a Brown and Caldwell engineer in a light plane directed the boat via two-way radio.

The aerial photography program was very successful in recording the surface manifestations of mass water movement. Information on changes in the water mass with depth was provided by the vertical profiles of temperature and salinity which were recorded aboard the boats.

Physical and Chemical Characteristics

The water flowing out of San Francisco Bay is less saline, more turbid, and depending on the season up to 10 deg F (degrees Fahrenheit) warmer than the ocean water. Measurements of salinity, water transparency and temperature can therefore be used to trace the movement of water masses, both on the surface and at depth. Dissolved oxygen is a water quality parameter which is of considerable importance to the marine environment, and its measurement served to document existing conditions.

Water density, as explained in Chapter 3, has a strong influence on the degree of initial dilution attainable in a rising jet of sewage effluent. Further, the density gradient in the water mass from top to bottom determines whether an effluent field will rise to the surface or remain submerged. Density is not measured directly, but is calculated from two measured parameters, salinity and temperature.

An instument string is lowered into the water to obtain a vertical profile of water mass characteristics. The string includes a captive electric current meter and probes for dissolved oxygen, temparature, conductivity, and depth.

The clarity of the water mass is a quality parameter with both esthetic and ecological significance. Quite obviously, clear water is more pleasing to view than turbid water, and background conditions of clarity must be determined in order to predict the deviation from background which may be caused by a waste discharge. The degree of light penetration is a function of water clarity which is directly related to the amount of photosynthesis which takes place in the surface water. The depth to which light can penetrate controls the growth of phytoplankton and therefore the food and oxygen production in the surface layer.

The boats used in this study served as surface platforms for the measurement of temperature, salinity, dissolved oxygen, water clarity, and wind direction and velocity. Temperature and salinity were measured with a Martek Model TDC metering system, and dissolved oxygen with a Martek Model DOA in-situ dissolved oxygen monitor. The probes for temperature, conductivity and disolved oxygen, together with a probe for depth measurement, were enclosed in a perforated plastic housing and attached to a multi-conductor underwater cable which in turn was connected to indicating instruments on the deck of the boat. The housing and probes were lowered by an electric winch to the desired depth and readings were recorded. In the office, readings of conductivity were converted to salinity by using conversion charts furnished with the instrument. All probes were standardized twice a day when the instrument systems were in use.

Water clarity was measured by Secchi disc. While the limitations of this device as a scientific instrument are well known, it was established in the course of this study that the Secchi disc does a good job in measuring visible differences in water clarity. Whenever a difference in water clarity could be observed, the Secchi disc measured a lesser depth in the water that the observer classified as "dirtier" and a greater depth in water that the observer classified as "cleaner". As an esthetic matter, observable differences in water clarity can be of considerable importance.

Wind direction and velocity were measured periodically with a hand-held anemometer and compass.

Current Measurements

A principal source of current data for this study was the data collected by the United States Coast and Geodetic Survey in San Francisco Bay and the Gulf of the Farallones during 1952, 1953 and 1954.[23] That study included measurements of currents throughout the San Francisco Bay System, and provided the basic data for the preparation of tidal current charts for San Francisco Bay. The stations in the Central Bay and Gulf of the Farallones which are of particular concern to this study are shown on Fig. 4-4. In addition to the USC&GS data, current measurements were taken during this study by several different methods.

A number of surface current measurements were obtained from the rate of movement of turbidity lines as recorded by photographs during the study of mass water movement. Other surface current measurements were derived from the shift in position of dye patches during the measurement of dye dispersion. Measurements of subsurface currents were taken by two different types of current measuring devices.

The first type of current meter used was a Hydro Products in-situ meter, which when anchored in place at the depth desired continuously records current direction and velocity. The in-situ meters were employed successfully on the

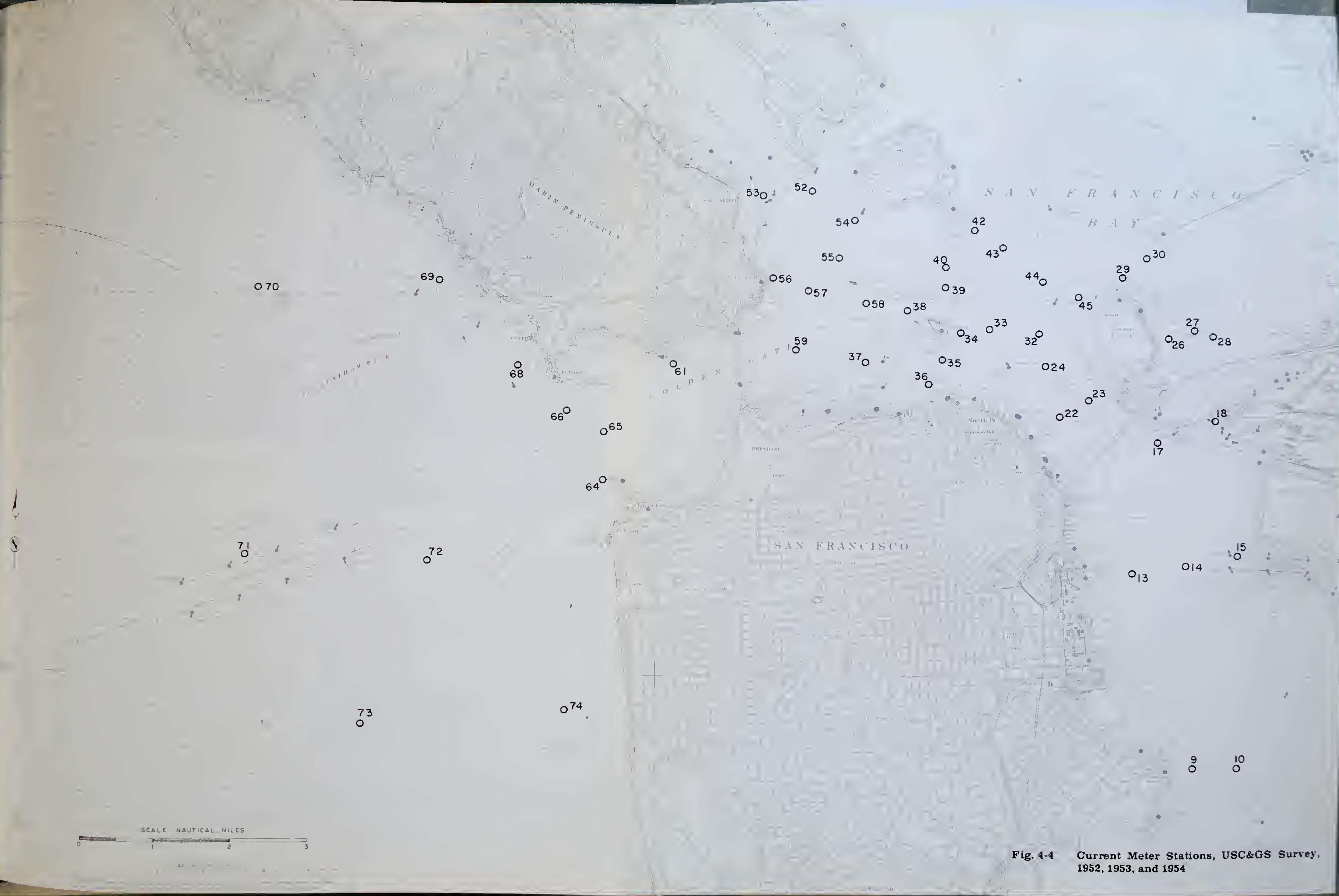
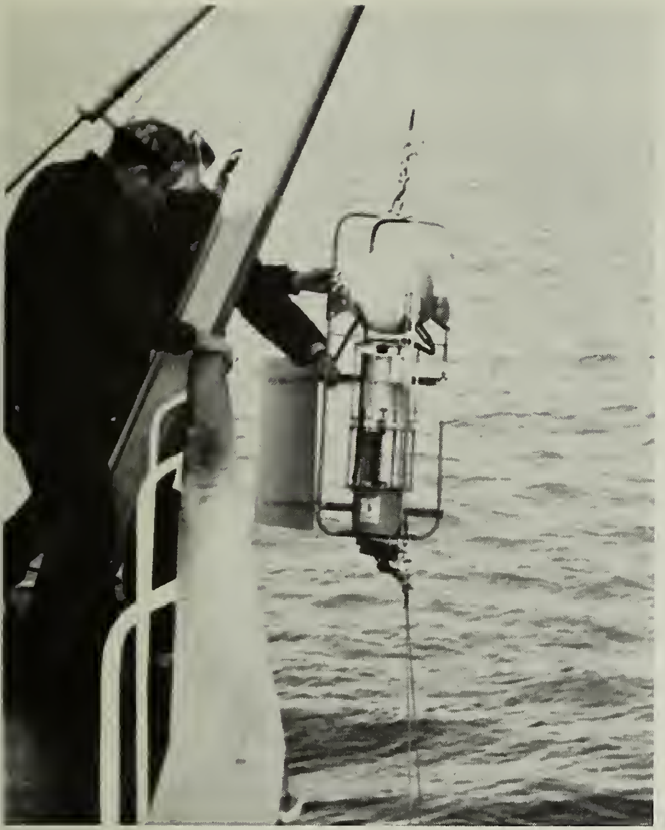


Fig. 4-4 Current Meter Stations, USC&GS Survey, 1952, 1953, and 1954



An in-situ current meter is lowered into the Gulf of the Farallones, where it will remain anchored for a full tidal cycle continuously recording current direction and velocity.

first cruise, but on the second cruise high seas prevented the recovery of the anchored meters. After the seas abated the meters could not be located, and the meters and current records for that cruise were permanently lost.

The metering system employed for the remainder of the study was a TSK type E-2 captive electric current meter with a deck readout of current direction and velocity, water temperature, and instrument depth. The TSK meter was lowered by winch from an anchored boat, with current measurements taken at the desired depths. Because of the complicated current regime which exists in certain areas around the Golden Gate, the more detailed current profiles obtainable with the captive meter provided information superior to that obtainable with the in-situ meters.

Any current meter must be selected for most accurate metering over a specific current velocity range, and some sacrifice in accuracy must be made outside that range. Available information showed the existence of very strong currents in the area to be covered by this study, and accurate measurement of maximum currents was deemed more important than measurement of minimum current velocities. In the case of the Hydro Products in-situ meters, the minimum current that could be accurately measured was about 0.25 knots. The TSK captive current meter provided no usable information on currents less than 0.2 knots.

Whenever shore points were visible, boat position was fixed by sextant shots (top) and plotted immediately (bottom).

Dispersion Studies

The purpose of the dispersion studies described herein was the definition of k, α , and m through field measurement in each of the oceanographic seasons. Referring to equations (1) through (5) on pages 18 and 19,

k = turbulent diffusion or dispersion coefficient, sq ft/hr,
α = so-called four-thirds law coefficient, and
m = the exponent of the relationship between scale and k.

A definition of k proposed by Brooks[15] and Fischer[24] states:

$$k = \frac{1}{2}\frac{d\sigma^2}{dt} \quad \textbf{(6)}$$

where σ = standard deviation of the concentration distribution, and
t = time

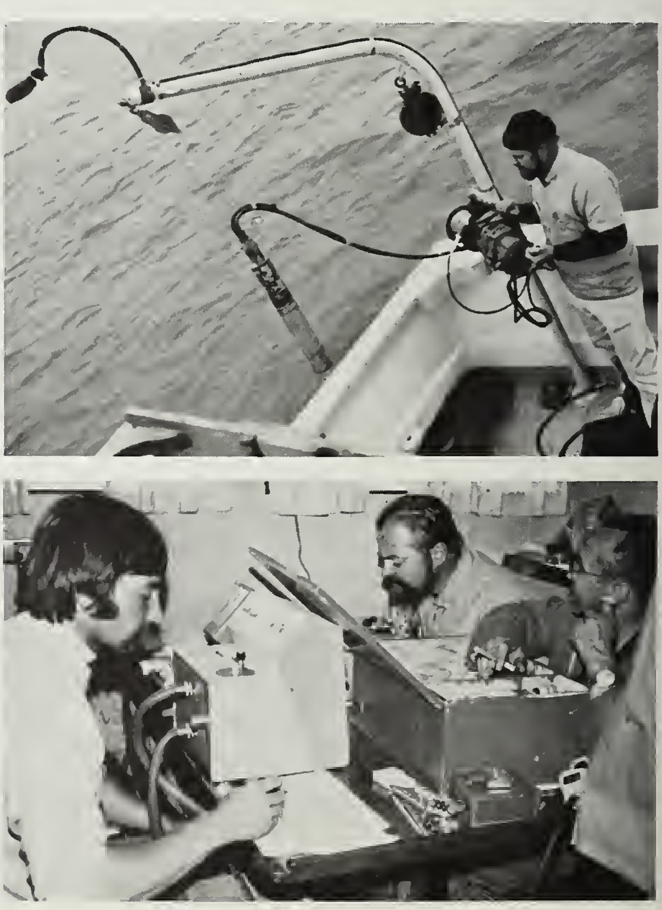
If a dispersing dye patch is used for experimental determination, the above equation can be used to compute dispersion coefficients from concentration profiles measured through the dye patch at successive times. The dye patch tracer technique employed by Brown and Caldwell in the Marin County sewerage study[25] was modified for use in the present investigation.

Field Procedure. Basically, the procedure employed involved the measurement of the rate of dispersion of a quantity of red fluorescent dye dropped in an area where a surface effluent field might logically be dispersed. The dye selected for the study was Rhodamine WT, and each drop consisted of 5 lbs of dye in a 20 percent acetic acid solution.

As the dye patch spread out through the mechanism of turbulent diffusion, the research vessel made periodic traverses of the patch in longitudinal and transverse directions, taking a continuous record of dye concentration along each transect. Vertical profiles were also made periodically to record the depth of the dye field. Since all transects were run at a controlled boat speed, the length of each transect could be determined by the time of travel. In addition, wherever possible, the transect length was checked by fixing the boat position at the start and finish of each transect. Boat position was fixed by sextant shots whenever shore points were visible. An independent check on transect length was obtained from aerial color photographs taken by the light plane which was

The R/V "Amigo" runs a transect through a dye patch in the Central Bay. Note the discoloration caused by the North Point effluent field near shore.

Dye concentration was measured by continuously pumping a water sample from a submersible pump (top) through a recording fluorometer (bottom, left).



directing the boat. Using the length of the boat for scale, it was possible to check quite precisely the dimensions of the visible dye patch.

Dye concentrations along each transect were recorded by a Turner Model 111 continuous flow recording fluorometer (Fig 4-5). A submersible pump, positioned by a power winch, was lowered to the desired depth, which for most horizontal transects was about three feet below the surface. The pump delivered a sea water sample continuously to the fluorometer. Before and after each cruise the fluorometer was calibrated in the laboratory with mixtures of dye and distilled water. After each cruise sea water collected on the cruise was checked in the laboratory to determine the correction factors for background interference with fluorometer readings. The results of the dye studies showed that the dye patch was visible from the air at dye concentrations of about 2 ppb (parts per billion). The limit of detection of the fluorometer was about 0.05 to 0.10 ppb, and the background level of fluorescent substances in the ocean water was about 0.05 ppb.

The dye patches tended to elongate in the direction of the current movement. As used in this study, the axis of the patch in the elongated direction is termed the major axis or x-axis, and the axis perpendicular to the current flow is termed the minor axis or y-axis. Vertical profiles of dye concentration were taken in the center of the patch, and these profiles are termed the z-axis. As a normal procedure, x, y and z axes were traversed successively until data collection was judged to be sufficient or until the process was interrupted by patch disappearance or navigational hazard.

Data Analysis. Dispersion coefficients were calculated by use of Equation (6). Integrating that equation yields:

$$2k(T_2 - T_1) = \sigma_2^2 - \sigma_1^2 \tag{7}$$

where T_2 = elapsed time from dye drop to measurement of transect being analyzed,
T_1 = elapsed time from dye drop to measurement of previous transect along the same axis,
σ_2 = standard deviation of dye profile at time T_2, and,
σ_1 = standard deviation of dye profile at time T_1.

Now the scale of the dye patch, L, is defined as

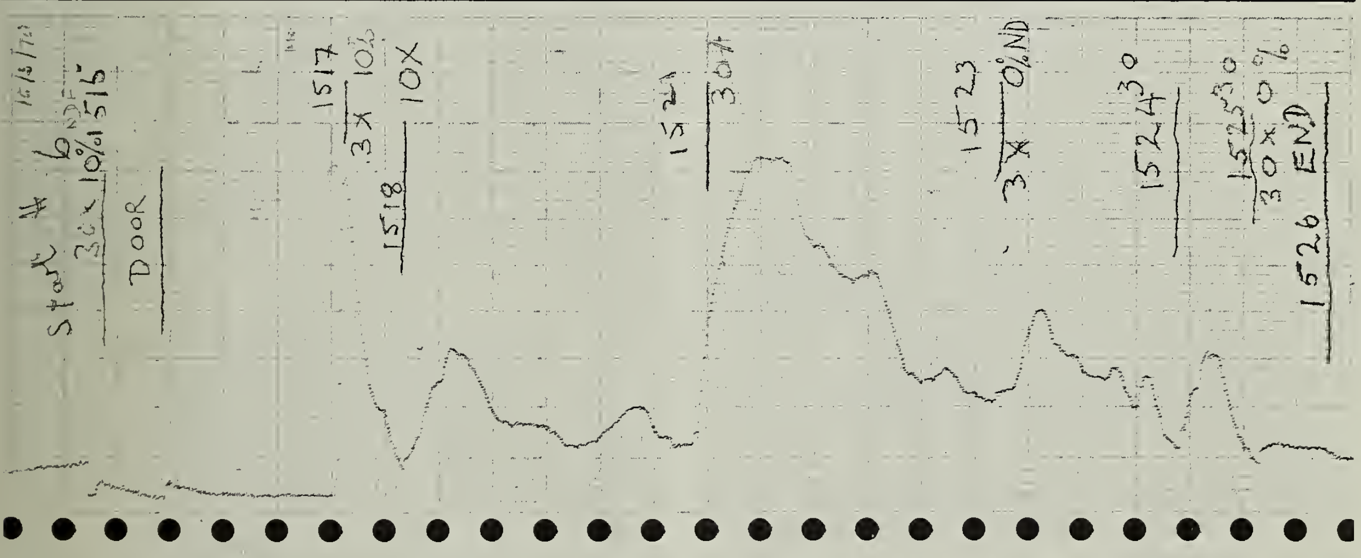
$$L = 2\sigma .$$

Therefore, equation (7) can be simplified to

$$k = \frac{L_2^2 - L_1^2}{8(T_2 - T_1)} \tag{8}$$

where L_1 = scale at time T_1, and
L_2 = scale at time T_2.

Fig. 4-5 **Typical Fluorometer Strip Chart Record of Dye Concentration in a Dispersing Dye Field**



Equation (8) is the basic equation used to develop values for k from the field data.

The values of k thus obtained pertain to the diffusion of the dye patch from time T_1 to time T_2 and were plotted against an index of the average scale during this interval, taken as

$$\frac{L_1 + L_2}{2}$$

The definition of scale used in this report ($L = 2\sigma$) is different from the definition used by Brooks ($L = 2\sqrt{3}\sigma$) as described on page 18 . This difference in definition requires the application of a correction factor to permit the use of the calculated coefficients in Brooks' equations for subsequent dilution.

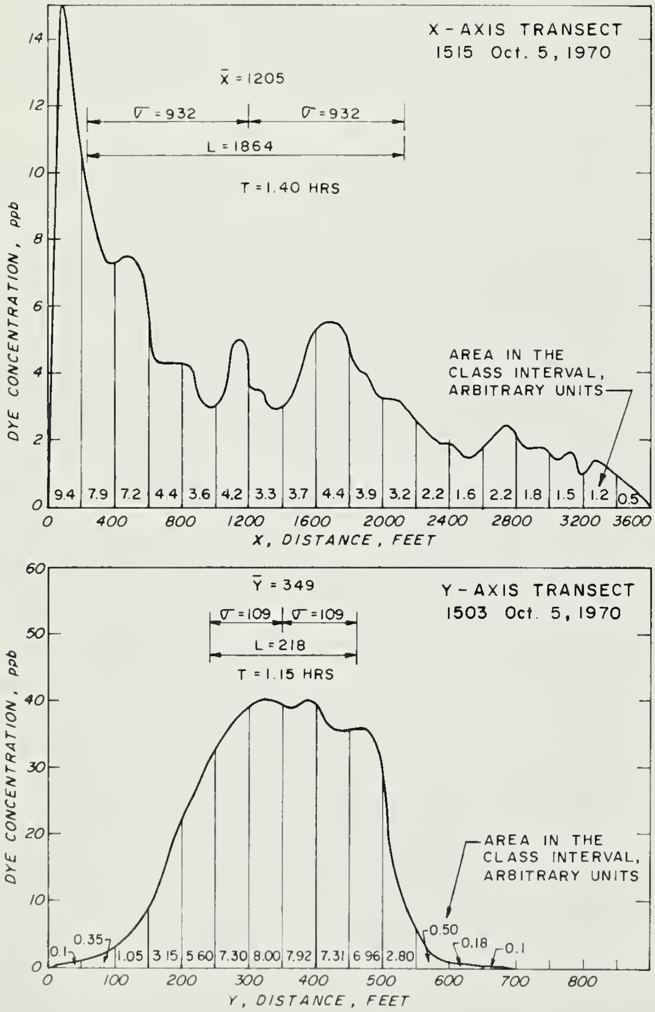


Fig. 4-6 **Histograms of Dye Concentration Along Major and Minor Axes of a Dispersing Dye Field**

The fluorometer strip chart records were analyzed by correcting for scale, temperature, and background fluorescence, and the corrected dye concentrations were then portrayed in histogram fashion as shown in Fig. 4-6. As the figure indicates, the dye did not always disperse in a normal distribution pattern. By standard statistical procedures, the arithmetic mean and standard deviation were computed from the histograms, and the dispersion coefficient was calculated using Equation (8). In the case of the first transect of a patch, T_1 is zero, and L_1 was taken as the patch size at the time discharge of the dye was completed. In the case of the vertical profiles, the water surface acts as an obvious boundary to vertical diffusion. To keep the scale definition consistent with the x and y distributions, a mirror image of the vertical distribution was projected as shown in Fig. 4-7.

Surface Drift

As described in Chapter 3, the movement of particulate matter in the surface water film may be quite different from the movement of the water mass as a whole. The method selected for defining the movement of particulates involved the release of quantities of old-fashioned milk bottle caps at planned locations and times. The milk bottle caps are waxed cardboard discs of a size which makes them readily visible along the beaches, and yet they have an extremely small

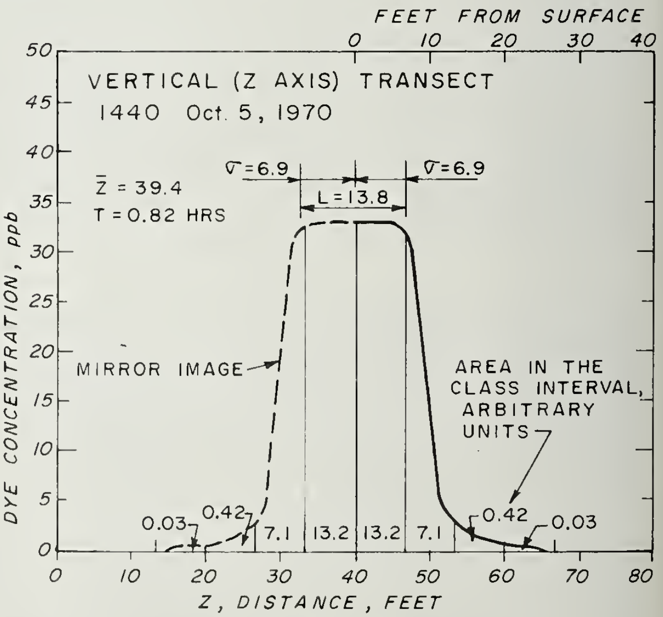


Fig. 4-7 **Histogram of Dye Concentration Along Vertical Axis of a Dispersing Dye Field**

area projecting above the water surface to catch the wind. Further, they are available in a wide variety of printed patterns to identify different release points and times.

Bottle caps were released in groups of 1500 at points which had been tentatively selected for submarine outfall evaluation. Where possible, releases were made at the tidal nodes for one complete tidal cycle. This planned pattern of release was occasionally modified to fit the required schedule of other investigations being conducted by the research vessel on the same day.

After the caps had been given time to drift ashore, approximately 20 miles of beaches and shoreline were walked by pickup crews who collected and catalogued as to type, number and location all of the caps which had drifted onto the shoreline. At least two sweeps were made of the shoreline, the first within about 48 hours after release and the second about a week after release. The shoreline covered included all of the areas which are considered to have major recreational significance, and provided spot sampling for areas of lesser significance or where the chances of finding drift indicators was considered to be less.

Surface drift surveys using milk bottle caps were conducted in June and October, 1970. In January, 1971 the collision of two Standard Oil tankers near the Golden Gate Bridge resulted in the release of several hundred thousand gallons of heavy fuel oil in the Golden Gate and Central Bay, providing additional information on the movement of floatable materials in the Central Bay and Gulf of the Farallones. Shortly after the spill occurred, the Environmental Protection Agency contracted with Texas Instruments to make three overflights of the slick area on successive days and record the position of the slick by infrared and ultraviolet remote sensing techniques. These overflights, combined with information from other sources on the locations where the oil came ashore, provided information on movement of floatables under winter conditions which could not otherwise have been incorporated in this study.

PHYSICAL OCEANOGRAPHY OF GULF OF FARALLONES

The Gulf of the Farallones (Fig. 4-8) fits only loosely the standard definition of a gulf, which is a portion of the sea partially enclosed by land. The western boundary of the gulf must be arbitrarily drawn, and for the purposes of this study is assumed to coincide with the western jurisdictional boundary of the Regional Water Quality Control Board, San Francisco Bay Region. Under this definition the Gulf of the Farallones includes all of the ocean area enclosed by the California coastline and a line drawn from Point Montara to the Farallon Islands, and thence northward to Point Reyes. This area covers approximately 600 sq mi (square miles) and comprises most of the continental shelf west of the Golden Gate. Water depth varies from a minimum of 23 ft over the bar north of the Golden Gate to a maximum of 300 ft north of the Farallon Islands. Immediately west of the Farallon Islands the bottom slope breaks sharply downward, and within a few miles reaches depths of 10,000 ft.

The area investigated most intensively in connection with this study is much smaller in size, comprising that portion of the gulf which is most strongly influenced by the tidal ebb and flow from San Francisco Bay. This area, which is one of major concern with regard to the disposal of sewage effluents from the City of San Francisco, is bounded on the west approximately by a line drawn from Rocky Point on the north to the San Francisco Lightship and then to Point San Pedro on the south.

A literature search revealed that very little oceanographic work has been reported in the area of immediate concern to this study. The U. S. Coast and Geodetic Survey in 1952-53 conducted extensive current measurements in San Francisco Bay, the Golden Gate, and westward to the outer edge of the bar. The report on these current measurements, unpublished, provided a major reference source for this study. A second report, prepared for the City of San Francisco by Eddy, Hyde, Kennedy and Reynolds in 1935[4] presents the results of float and drift bottle measurements at various release points in and around the mouth of San Francisco Bay.

The basic approach of the physical oceanographic work undertaken for this study was one of intensive investigation of the area during three representative seasons of the year, and cruises were accordingly scheduled for February, June, and October of 1970. Each cruise period collected data on mass water movement, currents, dispersion coefficients and the physical and chemical characteristics of the water mass. The latter included measurements of temperature, salinity, dissolved oxygen and water clarity. In addition, the June and October cruises collected information on the surface drift of floatable particulate matter.

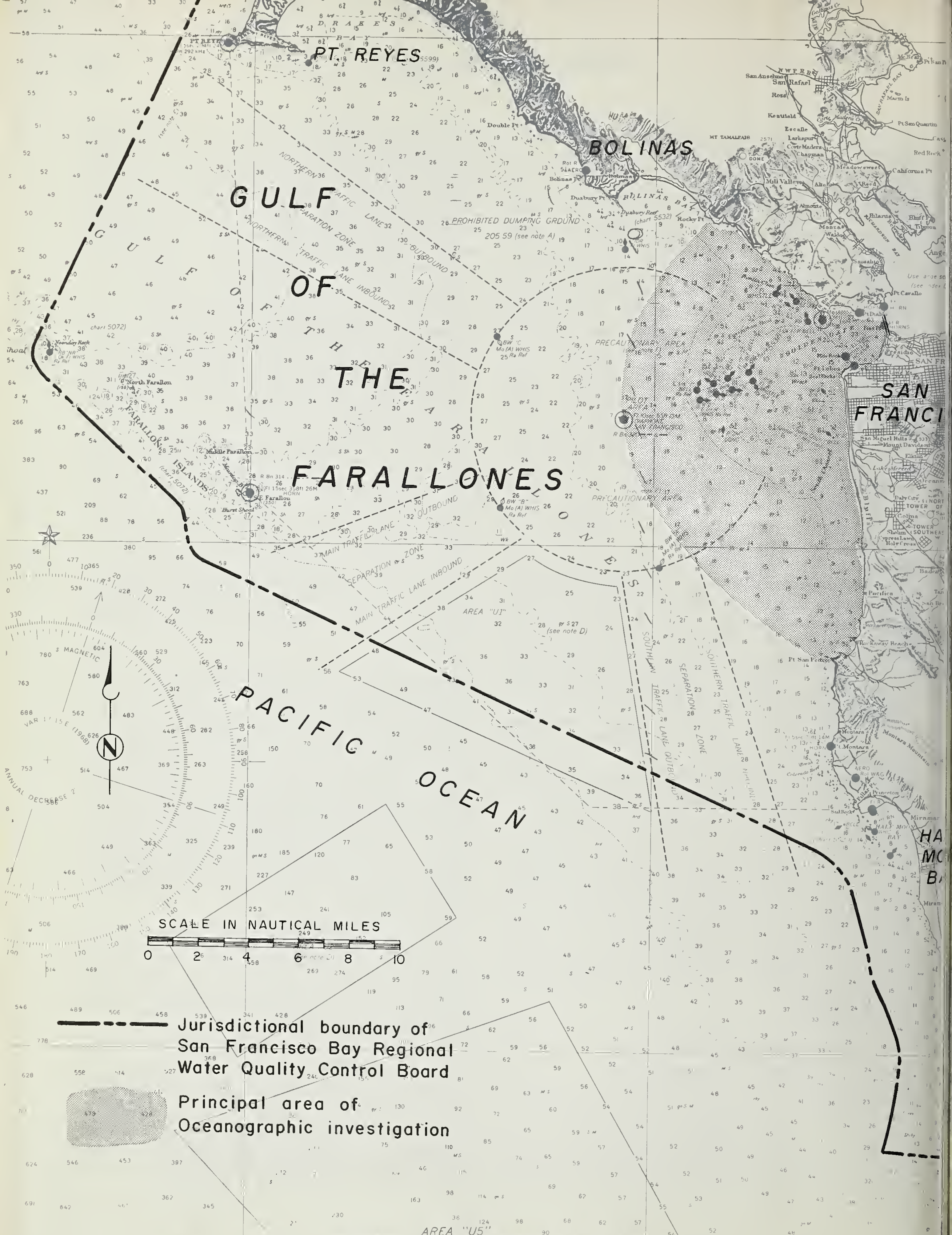


Fig. 4-8 **Oceanographic Study Area**

Winter Season

The cruises in February were scheduled during the Davidson current period, which in 1970 was also a period of high Delta outflow, averaging 72,000 cfs for the month. The cruises were planned to provide two periods of continuous observations over a complete tidal cycle. The first cruise, carried out on February 3-4, 1970, covered a period of maximum tidal amplitude and inequality. The second cruise on February 24-25, 1970, covered a period of equal tides of minimum amplitude.

Winter Season Mass Water Movement. Initial reconnaissance flights to record mass water movement were carried out in September, 1969 and January, 1970. Aerial photographs showed the general shape and magnitude of mass water movement on an ebbing tide (Fig. 4-9) and provided information on the best film types for recording the phenomenon. From this information a program of aerial photography was developed.

The pattern of outflow from San Francisco Bay shown on Fig. 4-9 for September, 1969 and January 1970 was repeated on each subsequent observation with some slight variations depending on the season. The basic pattern is one of westward and southward movement on the ebb, with water on the flood moving in first from the north around Point Bonita and from the south around Point Lobos. As the turbidity bulb moves west of the San Francisco Lightship, the western edge becomes indistinct. This may be a point of mixing with the prevailing oceanic current. The larger pattern on January 2 was caused by an ebb of greater amplitude than on September 30, coupled with increased surface outflow of fresh water from winter rains. The outflow pattern on January 27 showed a more pronounced southerly set than was observed at any other time in the course of the study.

The northern turbidity lines on September 30 and January 2 show the southerly offset caused by the flood current in Bonita Channel. The sharpness of the northern color line on January 27 indicates that the flood current from the north was passing underneath the less dense but more turbid surface layer. A sharp color line was found to be typical for cases where there was a large difference in relative movement between two adjacent water masses. The September 30 observations clearly show that the southern edge of the turbidity bulb was still moving southward even though the flood was well under way at the Golden Gate.

February 3 Cruise. On February 3 the information obtained from aerial photography was supplemented by data collected by the two boats, the Inland Seas and the Evie K. The combined information gave a clearer picture of the dynamics of mass water movement than could be obtained from aerial photography alone. Surface evidence of mass water movement is presented in Fig.4-10, and measurements which define the physical and chemical makeup of the water mass are reported in a subsequent section.

During February a heavy silt load moved through the San Francisco Bay system as a result of high fresh water runoff. The result in the Gulf of the Farallones was that frequently the pattern of discoloration caused by two successive ebbs could be observed at the same time. This was the case on both February 3 and February 24. Referring to Fig. 4-10, it will be seen that the color line from the short ebb on the night of February 2 persisted west of Lake Merced at the time the long ebb began on the morning of February 3. The long ebb moved strongly westward and less strongly southward, while the color line from the preceding short ebb continued to move southward ahead of the long ebb. Where the surface position of the color lines could be fixed geographically and temporally, average surface current velocity was computed. As shown on Fig. 4-10, the water mass moved westward on the surface at an average speed of about 1.7 K (knots) during the period of maximum ebb current. Surface movement southward ranged from about 0.76 K to 1.2 K. Currents in the Golden Gate were considerably higher. During this period of high fresh water runout, flood currents at the surface in the Golden Gate

The speed of the westerly surface current on an ebbing tide in wet weather is demonstrated by the wake behind a channel marker buoy five miles west of the mouth of the Golden Gate.

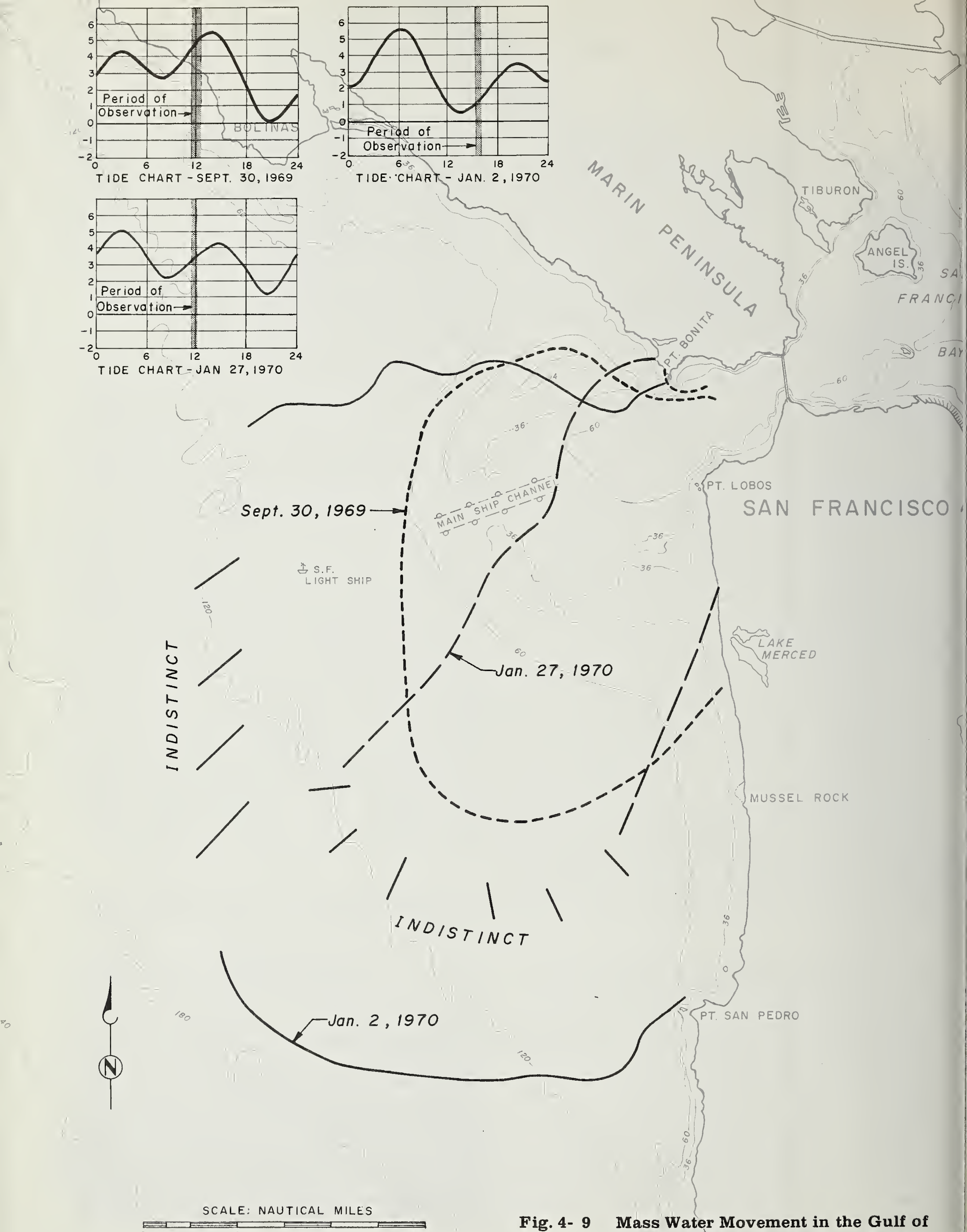


Fig. 4- 9 Mass Water Movement in the Gulf of the Farallones, September, 1969 and January, 1970

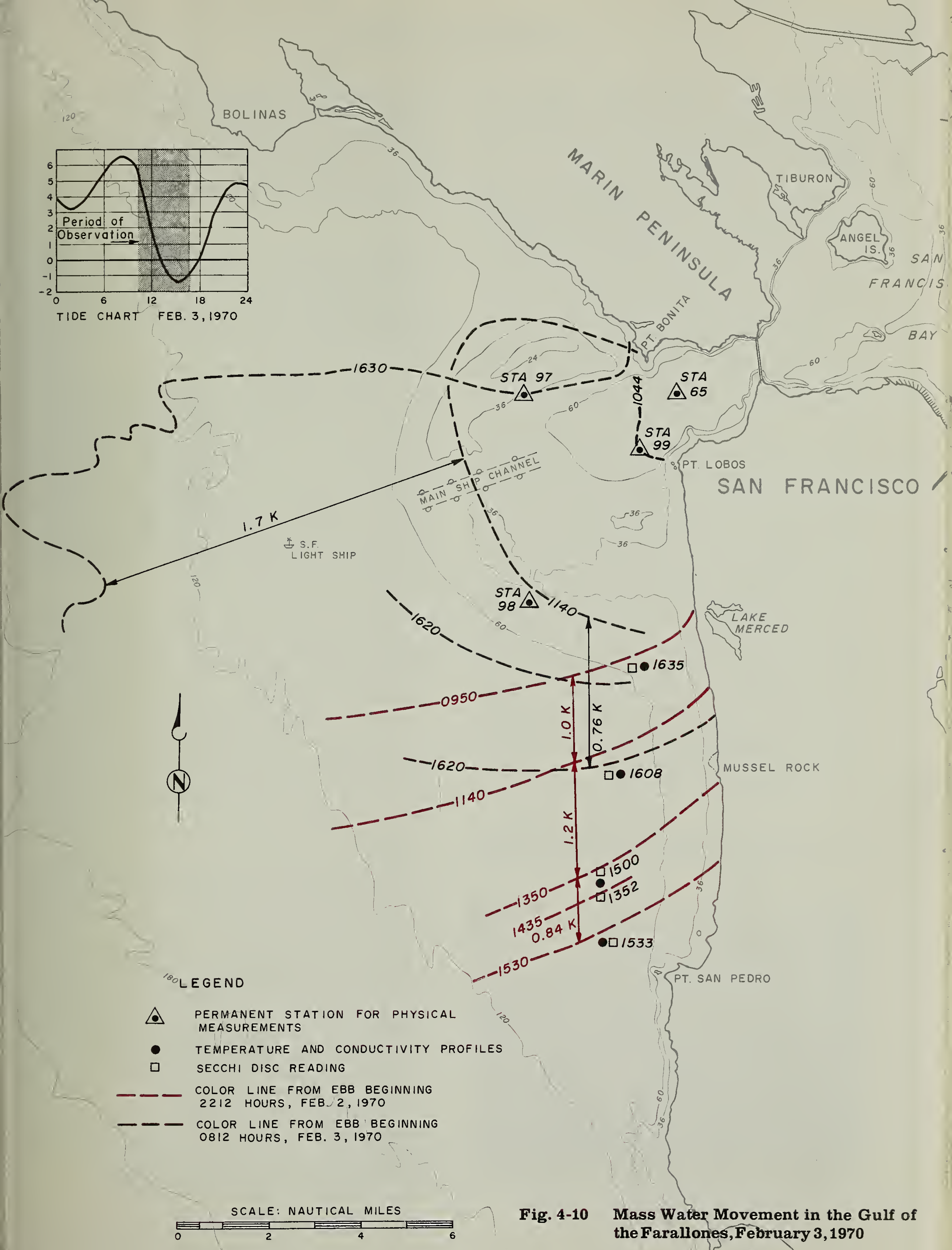


Fig. 4-10 **Mass Water Movement in the Gulf of the Farallones, February 3, 1970**

were either brief or non-existent. Conversations with charter boat captains and fishermen confirmed the fact that a continuous surface ebb through the Golden Gate is not uncommon during the winter.

Another phenomenon noted during February observations was the development of successive waves of turbidity on a single ebb, with each wave more turbid than the preceding one. This accounts for the fact that there are two color lines fixed as to location at 1620 hrs (hours) on February 3.

February 24 Cruise. Observations of mass water movement on February 24, 1970 covered a complete flood tide. As shown in Fig. 4-11, turbidity lines from the early morning ebb remained visible throughout the period of observation. The movement of color lines clearly showed the pattern of water movement on a flood tide, and this same pattern was observed repeatedly throughout the study. The early morning ebb moved strongly to the west and south in much the same manner as had been observed previously. Also as previously observed, the first evidence of the flooding tide was in Bonita Channel, where the color line was pushed south by the developing flood. To the south of the Golden Gate clear ocean water welled up through the trubid layer from the preceding ebb and flowed north near shore and around Lands End into the Gate. The sharpness of the color line, which persisted in a V-shape near Lands End even after the afternoon ebb was under way, showed that the clear ocean water was flowing northward and ducking under the less dense top layer, The effluent plume from the North San Mateo County Sanitation District outfall, which was visible from the air west of Lake Merced, showed that the northward flow of water along the coast continued after the color line from the afternoon ebb had begun to move southward down the coast. At the end of the flood clearer water had moved in from the north and south, plainly cutting off the turbidity bulb from the morning ebb.

An aerial photograph looking toward the Golden Gate at end of flood on February 24, 1970 shows that the turbidity bulb from the preceding ebb has been cut off by clearer water flooding from the north and south near shore. The new ebb line can be seen at the mouth of the Golden Gate.

Winter Season Mass Water Movement Summary. During the period of high fresh water runoff in the San Francisco Bay system, tidal outflow from the Bay moves strongly westward and southward. Because the water from the bay is less saline and therefore less dense than the ocean water, tidal outflow occurs primarily as a surface layer. Kaiser Engineers[2] estimated the volume of the tidal prism at 50 x 10^9 cu ft. If this volume is assumed to be contained within the color line shown on Fig. 4-11 at 1010 hrs, then the average depth of the surface layer from the morning ebb on February 24 was about 7.5 ft. Considering the fact that a great deal of mixing and diffusion into the underlying ocean waters had to take place in the eight hours from start of ebb to 1010 hrs, this figure does not appear inconsistent with density profiles reported in a later section.

Surface flood tides in the Golden Gate are abbreviated in winter, and during periods of very high fresh water outflow may be absent altogether. Most of the flooding tidal prism therefore consists of denser bottom water. Combined with the fact that much of the water on the flood comes from the north through Bonita Channel and from the south around Lands End, this means that a very small percentage of the ebbing tidal prism returns to the bay on the following flood. Some of the ebbed water undoubtedly mixes with the underlying layer and returns to the bay on subsequent floods.

The effect of tidal flow extends as far as 15 mi to the west and 10 mi to the south of the Golden Gate. Within this area there is very little evidence that oceanic currents exert any significant effect on mass water movement.

Within about 24 hrs after passing through the Golden Gate, color differences fade. This may be due to sedimentation of the suspended matter or mixing with the underlying layer or both. Since turbidity lines could not be distinguished after the second ebb, the fate of the water mass more than about 24 hours after ebbing from the bay could not be determined. It is assumed that after 24 hrs the ebbed water mass has spread to a point where its further movement is influenced primarily by the general oceanographic characteristics of the coastal waters as described previously.

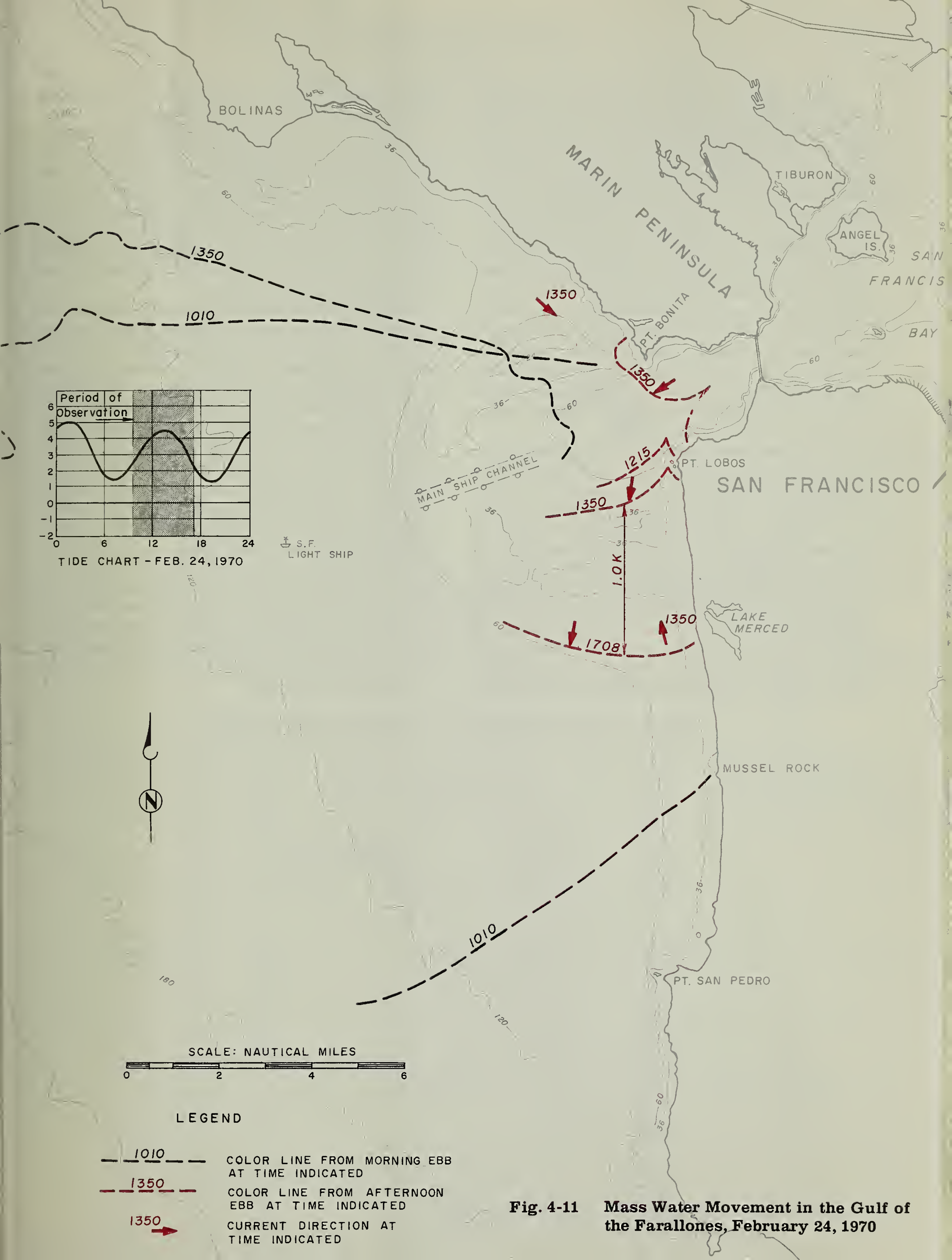


Fig. 4-11 Mass Water Movement in the Gulf of the Farallones, February 24, 1970

Winter Season Physical-Chemical Characteristics. Certain seasonal phenomena exert major influence on the physical-chemical makeup of the waters of the Gulf of the Farallones during the winter months. Ocean temperatures are at their lowest values for the year, and temperature stratification is minimal. Fresh water outflow from the San Francisco Bay drainage is at its annual high, which means that salinity and density in the area affected by San Francisco Bay outflow are at their annual low values. Since the fresh water tends to flow out on the surface, the water mass is markedly stratified. During this period Central San Francisco Bay, the Golden Gate and the ocean area immediately outside the Gate display the classical characteristics of a partially mixed estuary with a two-layer flow pattern. Dissolved oxygen values are close to saturation at all depths.

The geographical locations of physical-chemical measurements during the month of February are shown on Figs. 4-10, 4-12 and 4-13. The latter two figures also show the location of dye dispersion studies performed during the February cruises, Analysis of the dye work is described in a later section on dispersion studies. The work plan on both February 3-4 and February 24-25 called for two boats to operate in the study area at the same time. On the first cruise the Inland Seas made the continuous rounds of the permanent stations for 24 hrs, while the Evie K performed dye studies, took biologic samples and made physical-chemical measurements at stations of opportunity during the daylight hours of February 3.

On the second cruise, the Inland Seas was to remain anchored at permanent station No. 99 for 24 hours while the Fisherman's Grotto No. 9 made the rounds of the other stations and performed the dye study work. On the night of February 24 the seas began to rise and work became increasingly difficult. The cruise was cut short on the following day due to loss and damage of equipment and hazardous working conditions.

Graphs of salinity, temperature, density and dissolved oxygen plotted against depth are presented in Volume 2, Data Supplement, for each series of observations. With two boats operating in the study area, it was possible to get enough data at different points and approximately the same time to permit the plotting of salinity profiles through the study area. The locations of the profiles are shown on Fig. 4-14 and the profiles themselves are presented in Figs. 4-15 through 4-18. The profiles reveal a number of interesting characteristics of the water outside the Golden Gate during the winter season.

Where Secchi disc readings were taken, the values are plotted above the salinity profiles. The Secchi disc information was correlated with data on color lines recorded by aerial photography of water masses. A complete list of all Secchi disc observations recorded during the February cruises is presented in Table 4-1.

Table 4-1 Winter Season Water Clarity, Gulf of the Farallones

Date	Time, PST	Location of reading	Reference figure	Secchi disc, feet
February 3, 1970		Permanent stations		
	0900	Station 98	4-12	4.0
	1030	Station 97	4-12	3.0
	1610	Station 95	4-12	2.0
	1708	Station 97 - Outside color line	4-12	6.0
	1715	Station 97 - Inside color line	4-12	1.5
		Random stations		
	0905	See reference figure	4-12	6.0
	1022	See reference figure	4-12	4.0
	1206	Outside color line	4-12	6.0
	1223	Inside color line	4-12	5.0
	1352	Outside color line	4-10	12.0
	1500	Inside color line	4-10	10.0
	1533	Outside color line	4-10	15.0
	1608	See reference figure	4-10	14.0
	1635	See reference figure	4-10	9.5
February 24, 1970		Permanent stations		
	1340	Station 99	4-13	5.5
	1515	Station 99	4-13	5.5
		Random stations		
	0745	See reference figure	4-13	2.9
	1145	See reference figure	4-13	4.0
	1446	See reference figure	4-13	8.0
	1608	See reference figure	4-13	7.0

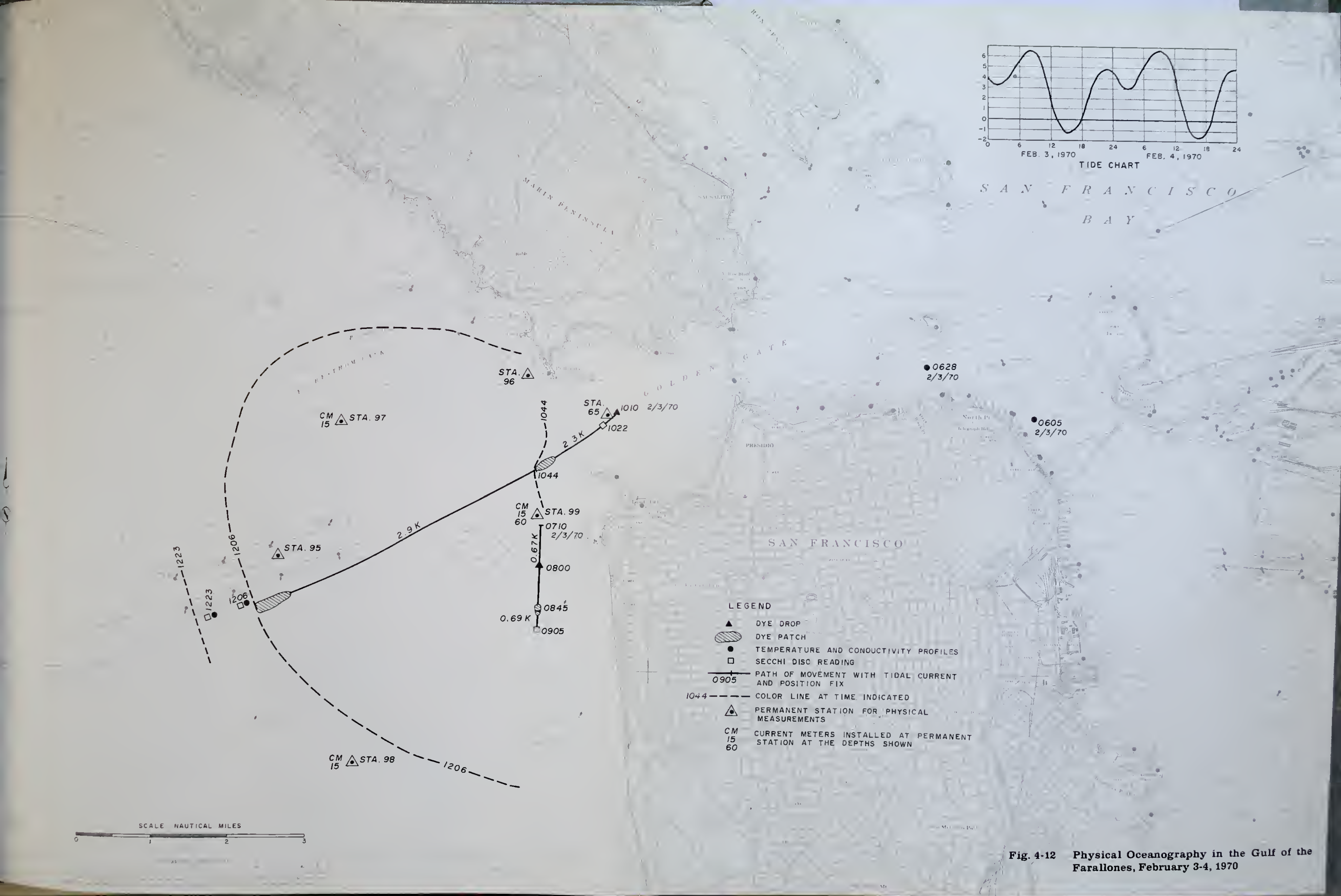


Fig. 4-12 **Physical Oceanography in the Gulf of the Farallones, February 3-4, 1970**

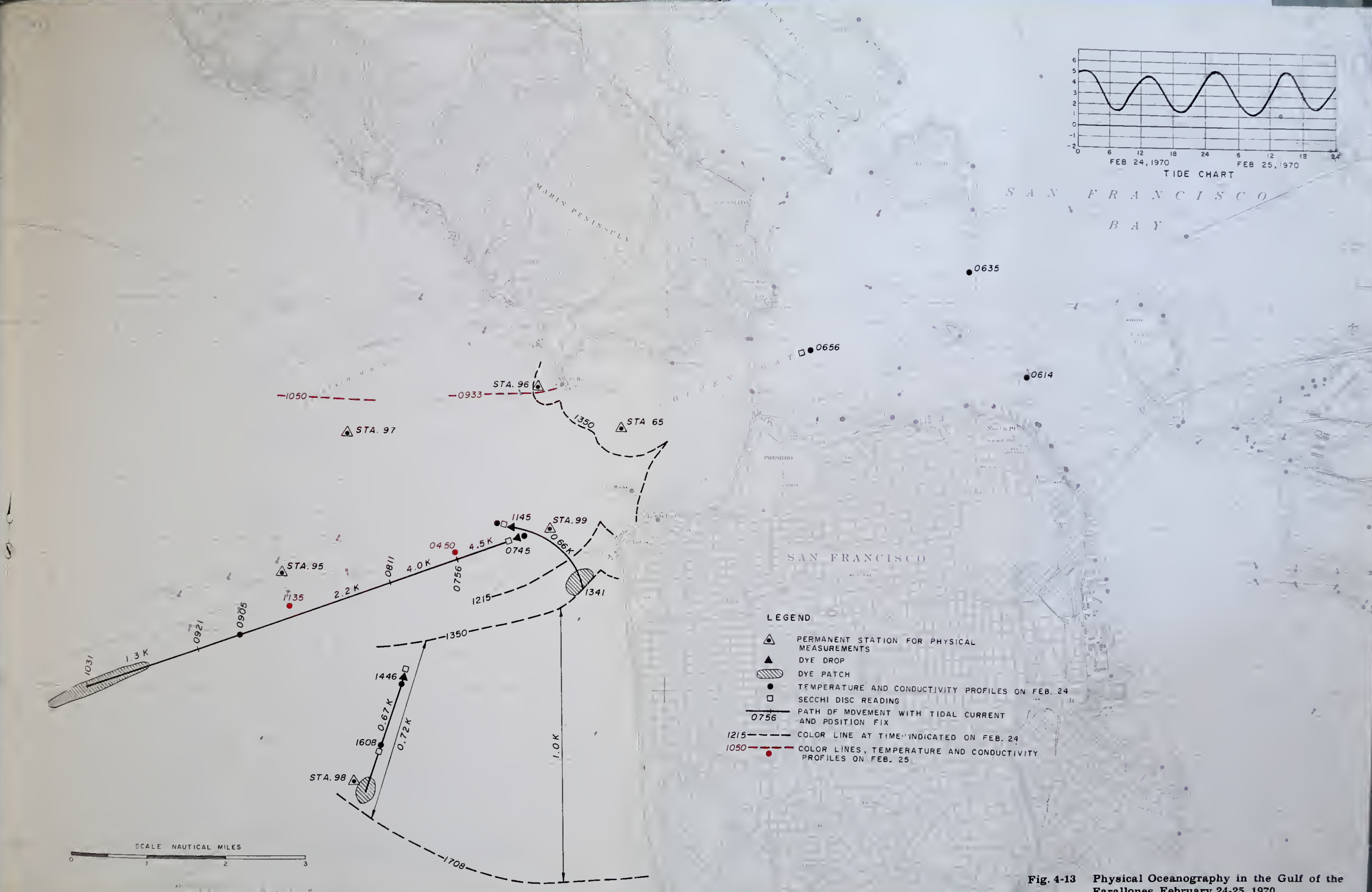


Fig. 4-13 **Physical Oceanography in the Gulf of the Farallones, February 24-25, 1970**

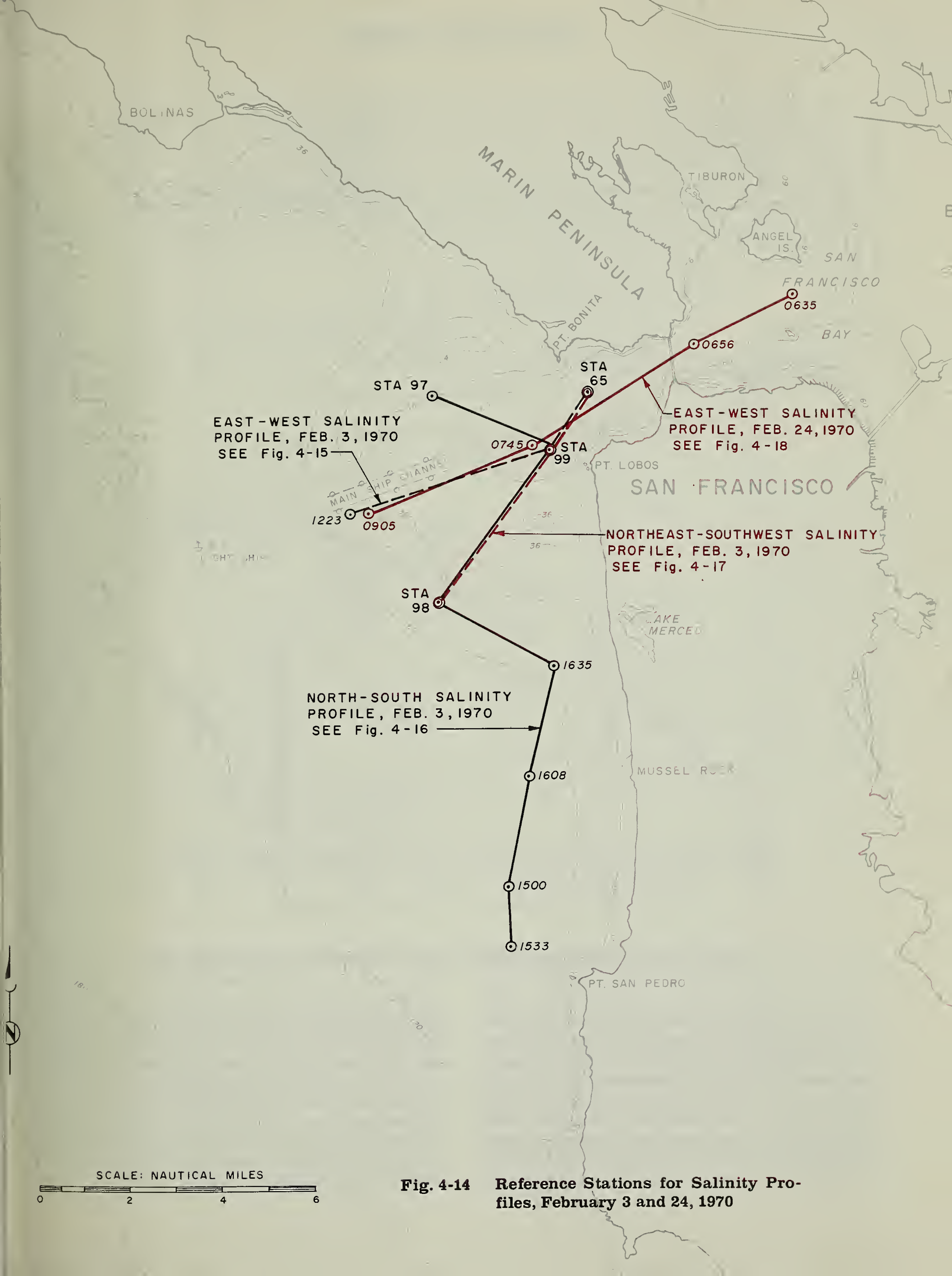

BOLINAS
MARIN PENINSULA
TIBURON
ANGEL IS.
SAN FRANCISCO BAY
PT. BONITA
STA 65
STA 97
STA 99
STA 98
0635
0656
0745
0905
1223
1635
1608
1500
1533
EAST-WEST SALINITY PROFILE, FEB. 3, 1970 SEE Fig. 4-15
EAST-WEST SALINITY PROFILE, FEB. 24, 1970 SEE Fig. 4-18
NORTHEAST-SOUTHWEST SALINITY PROFILE, FEB. 3, 1970 SEE Fig. 4-17
NORTH-SOUTH SALINITY PROFILE, FEB. 3, 1970 SEE Fig. 4-16
MAIN SHIP CHANNEL
PT. LOBOS
SAN FRANCISCO
LAKE MERCED
MUSSEL ROCK
PT. SAN PEDRO
N
SCALE: NAUTICAL MILES
0
2
4
6

Fig. 4-14 Reference Stations for Salinity Profiles, February 3 and 24, 1970

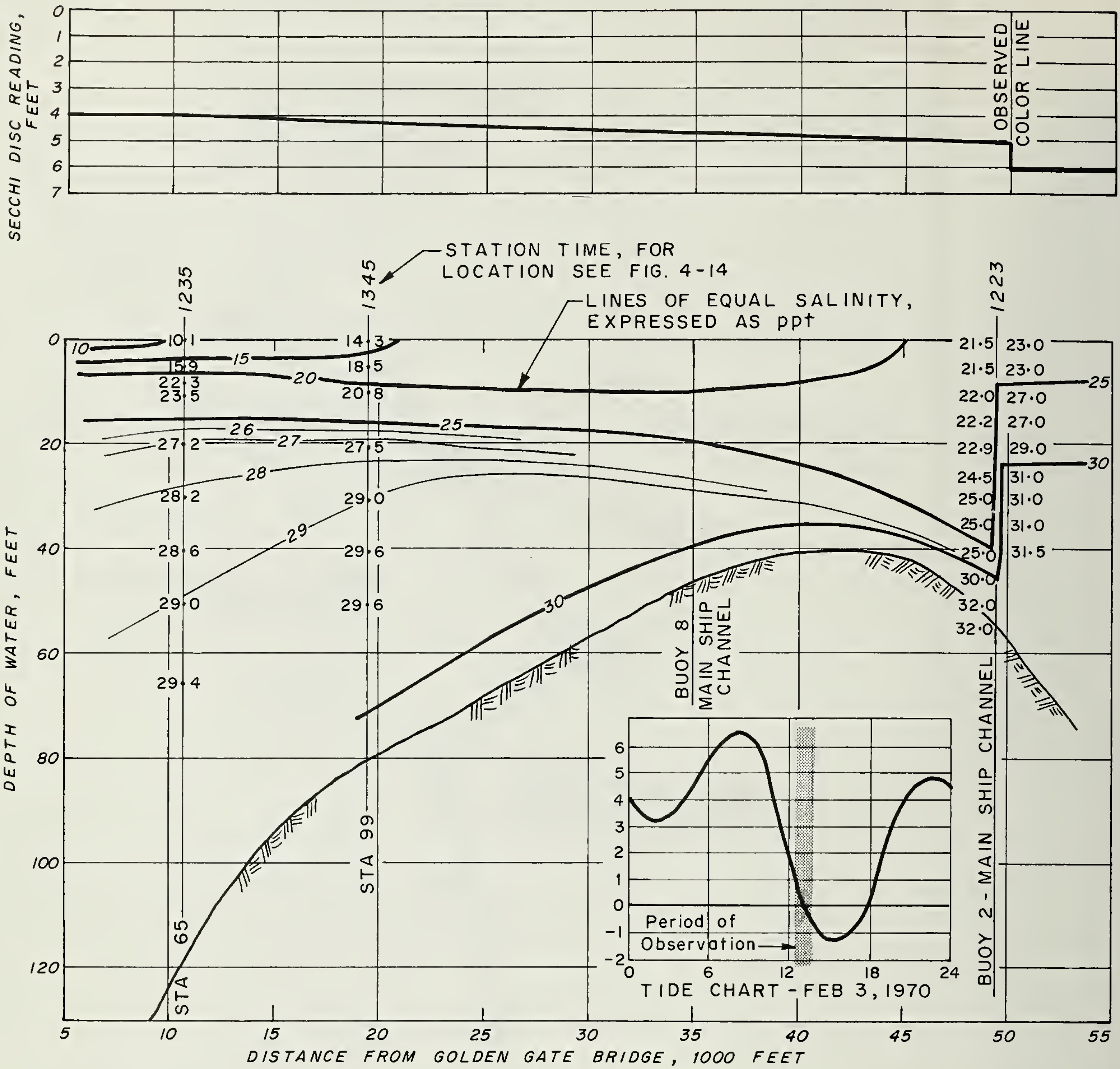


Fig. 4-15 East-West Salinity Profile, Gulf of the Farallones, February 3, 1970

Fig. 4-15 is a profile measured west from permanent station No. 65 at about the middle of an ebb tide of maximum amplitude. As the profile shows, fresh water was flowing westward through the Golden Gate in a surface layer with a depth of less than five feet. As the tidal flow moved westward, the fresh water was mixed with the more saline underlying ocean water. By the time the front of ebbing water had passed over the bar near the main shipping channel it was advancing on a broad vertical front of fairly uniform salinity about 40 ft deep. The color line at the front was plainly visible, though the difference in surface salinity across the front was not great. The salinity of 21.5 ppt (parts per thousand) east of the color line and 23.0 ppt west of the color line shows that a surface layer of fresh water from preceding ebbs persisted ahead of the moving tidal front.

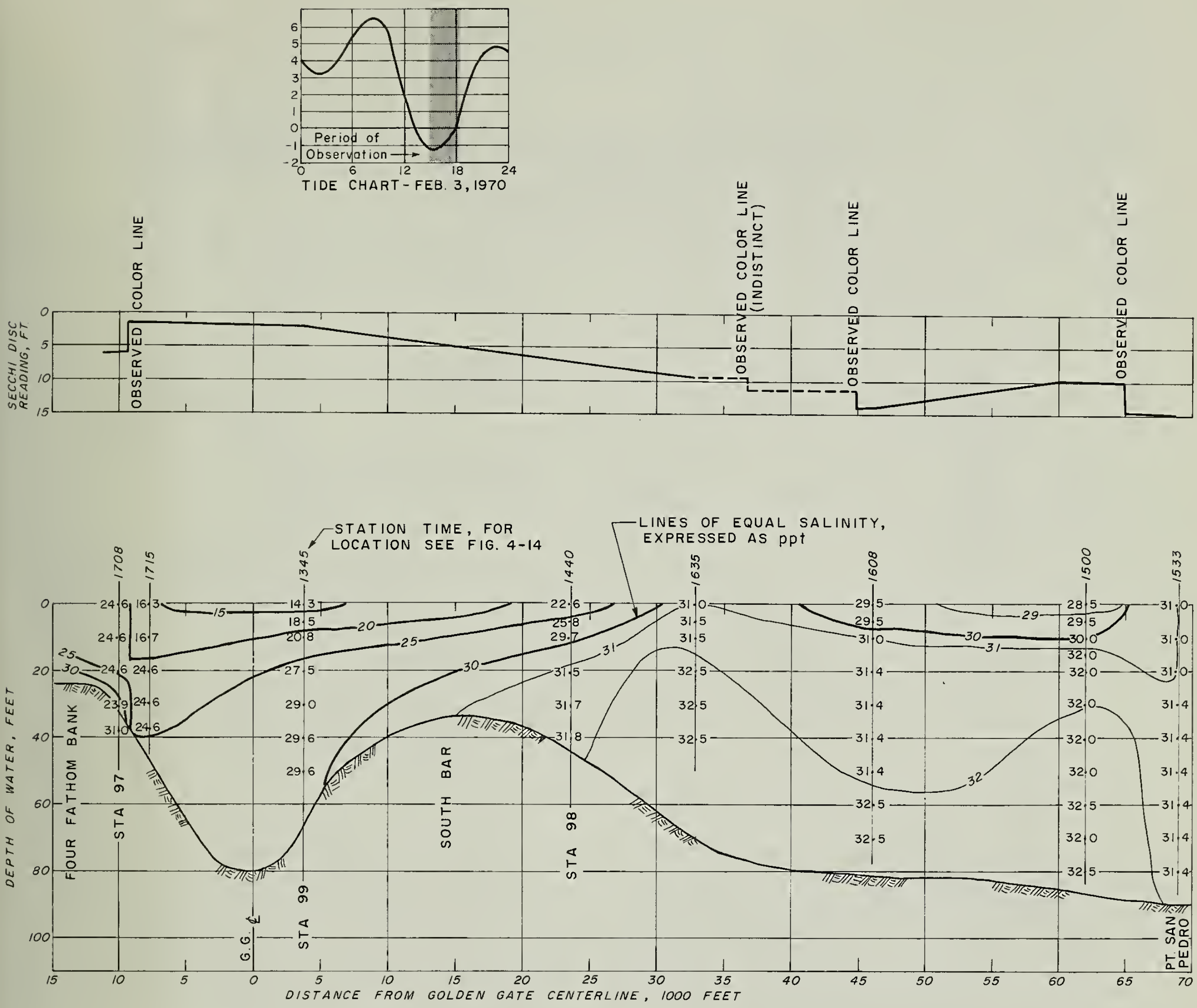


Fig. 4-16 North-South Salinity Profile, Gulf of the Farallones, February 3, 1970

A north-south profile from the north bar to Point San Pedro is shown in Fig. 4-16. Shown for an average time about three hours later than the profile in Fig. 4-15, the north-south profile shows some distinct differences between southern and westward movement. To the north the developing flood from the north was holding the ebbed water mass on a broad vertical front. The low salinity of the water mass to the north of the color line (24.6 ppt) shows that the flood from the north contained a significant amount of fresh water from previous ebbs. To the south two distinct masses of fresh water overlaid the ocean water in a thin layer. Near Point San Pedro the water mass from the previous ebb formed a layer about 10 ft deep, with salinity approaching that of the underlying ocean water. Over the south bar the fresher water from the ebb just ending was overriding the ocean water in a thinning layer. Just south of the south bar water of near oceanic salinity had welled to the surface. This upwelling of clear ocean water from the south near shore was noted repeatedly in succeeding observations of the developing flood tide.

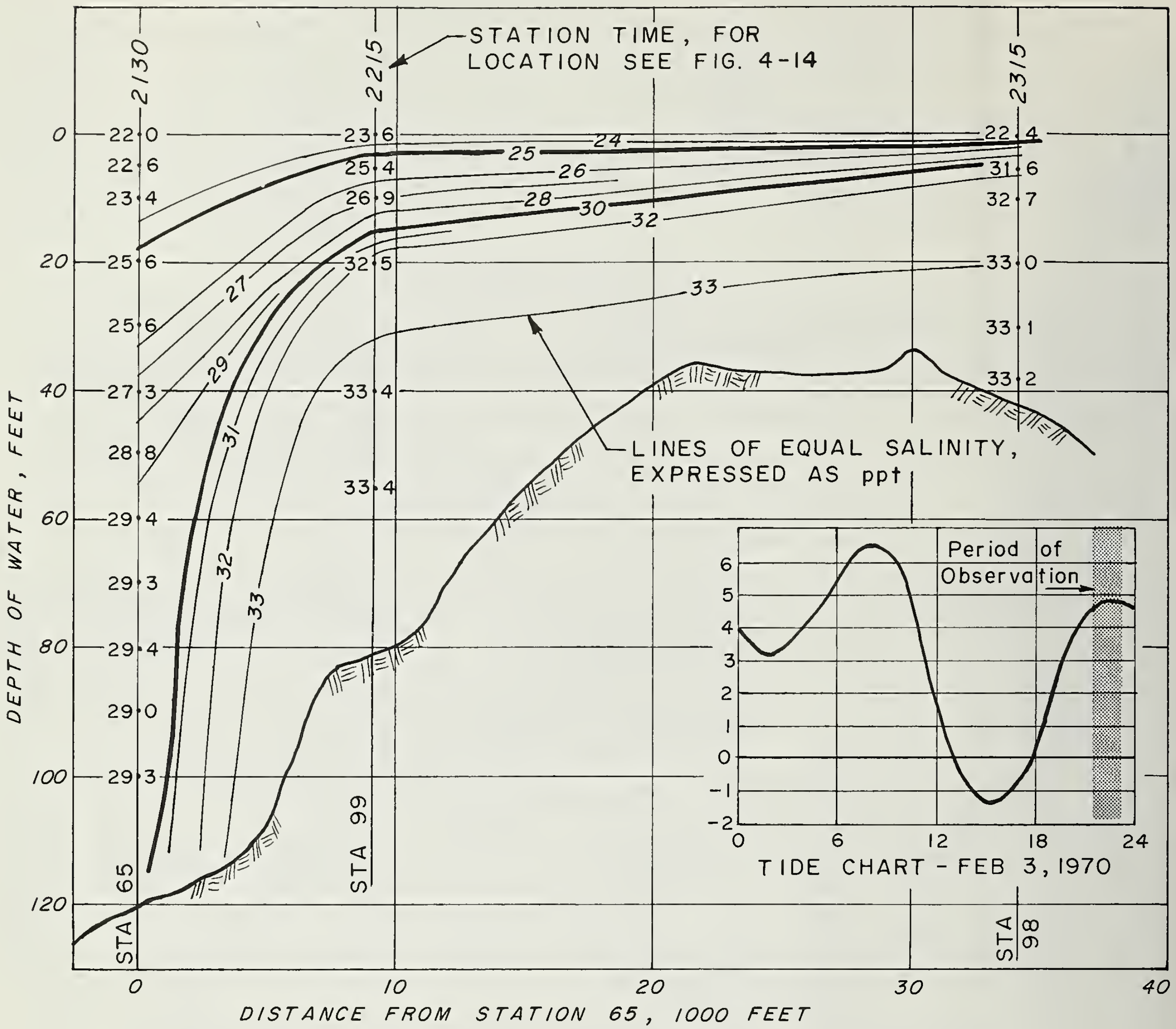


Fig. 4-17 **Northeast - Southwest Salinity Profile, Gulf of the Farallones, February 24, 1970**

Fig. 4-17 shows a salinity profile from northeast to southwest at about maximum flood current following the ebb described in Figs. 4-15 and 4-16. This figure shows that new ocean water had flooded across the bar at depths below about 15 ft and was moving toward the mouth of the Golden Gate on a broad vertical front, leaving the top layer of low salinity water substantially unchanged.

The final profile (Fig. 4-18) presents a profile from inside the bay through the Golden Gate and out to the bar. This profile, taken on February 24, confirms the information shown on Fig. 4-15. Minimum surface salinities were higher on February 24 because the ebb tide was of lower amplitude and because fresh water runout from the bay system was diminishing.

Dissolved oxygen profiles during the February cruises showed a marked uniformity at all stations and at all depths. Virtually all readings fell within the range of 8 to 9 mg/l with a minimum value of 7.8 mg/l and a maximum of 9.2 mg/l.

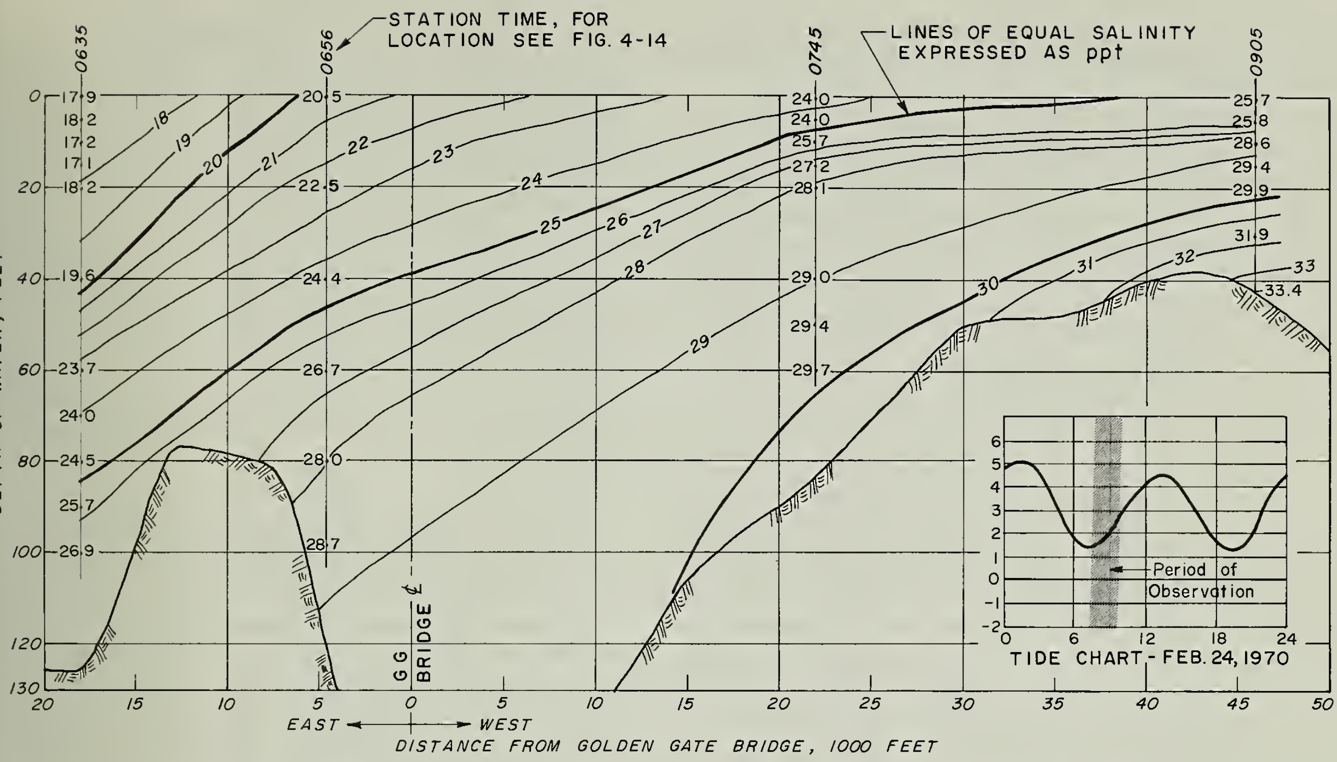


Fig. 4-18 **East - West Salinity Profile, Central Bay and Gulf of the Farallones February 24, 1970**

Winter Season Currents. The most impressive single fact about currents measured during the winter season is the dramatic difference between currents at the surface and currents even a few feet below the surface. On Febraury 3 (Fig. 4-12) a dye drop was made at 0710 near Station 99, where two current meters were installed at depths of 15 and 60 ft. Keeping in mind the fact that current reversal normally occurs at the Golden Gate about *one* hour after high *or* low water, 0710 hrs should have been about maximum flood current. However, the dye patch began immediately to move southward at a speed of about 0.7 K indicating that the surface current was ebbing. A dye drop at 1145 hrs on February 24 (Fig. 4-13) behaved similarly. Dropped to the west of Station 99 at about maximum flood, the patch moved toward the mouth of the Gate, then veered southerly and moved south parallel to the shoreline.

At Station 99 the current at 15 ft depth on February 3 was flooding at about 0.8 K until 0900, when a southerly ebb current developed. At 60 ft depth the southerly ebb current did not begin until nearly 1000.

A second dye drop was made in the Golden Gate at 1010 hrs on February 3, at about the start of the ebb as identified by tidal stage. Surface current in the Gate was already ebbing at a speed of 2.3 K. At about 1100 hrs the dye patch passed Station 99 at a surface speed 0.5 K greater than recorded by the current meter at 15 ft depth.

On February 24 the surface ebb current at the mouth of the Golden Gate (Fig. 4-13) was measured at a maximum value of 4.5 K. This was for a tide of lower amplitude than February 3, and it is possible that the maximum surface ebb current on February 3 was in excess of 4.5 K. The maximum ebb current measured at Station 99 at 15 ft depth was only 1.9 K, which was less than the maximum flood current of 2.2 K. It is possible that the anchored current meter string could not accurately record the maximum ebb currents because the bouyed equipment string was tilted too far out of vertical by the strong currents. However, even making allowance for some inaccuracy the data still indicate that there is a difference in current velocity of as much as 2 K between the surface and a depth of 15 ft. This is borne out by the fact that surface phenomena all showed a strong, nearly continuous westward movement on the surface, whereas the current data from all stations at 15 ft depth show a more normal pattern of ebb and flood.

Contained in Volume 2, Data Supplement, are graphs of advective flow for selected current measurements. These graphs indicate the direction and distance in nautical miles that water passing the meter would be moved by the measured currents during a 25-hr tidal cycle. Referring to the advective flow graphs for February 3, 1971, it will be seen that Station 99, 15 ft depth, showed a pattern of flow that was fairly well balanced between flood displacement to the northeast and displacement to the west and southwest on the ebb.

The advection pattern for the current meter installed at 15 ft depth at Station 97, just inside the north bar, was also at variance with the observed surface phenomena. Ebb currents showed a strong unidirectional component to the northwest, about 45 degrees off from the westerly ebb movement on the surface. The current record at Station 97 is four hrs short of covering a complete tidal cycle, and the missing records are from the flood phase. If complete, the displacement diagram would show a predominance of flood displacement to the southeast over ebb displacement to the northwest at the 15 ft depth.

At Station 98, just outside the south bar, current velocities at the 15 ft depth were much lower than at the other stations measured, ranging from 0.4 to 0.9 K. The displacement diagram shows a slight predominance of flood over ebb at 15 ft. Surface displacement, as demonstrated by the movement of color lines, was strongly to the south and southwest past Station 98.

Only one current meter, at Station 99, was installed below 15 ft, and that meter recorded current direction but unfortunately failed to record velocity. However, the data show that at 60 ft depth the current was flooding 69 percent of the time and ebbing 31 percent of the time.

In summary, the over-all picture of currents around the mouth of the Golden Gate during the season of high fresh water outflow is consistent with the salinity profiles presented earlier. A thin layer of low salinity and density moves rapidly and almost continuously westward and southward. The depth of this surface layer is probably less than 10 ft, and certainly less than 15 ft. At 15 ft depth a fairly balanced pattern of ebb and flood prevails, and near the bottom flood currents predominate. This is a typical circulation pattern for a positive estuary, with a predominate flow of low salinity water outward on the surface and a predominate flow of high salinity ocean water inward near the bottom. This circulation pattern was confirmed by the U. S. Geological Survey in a 1970 report on the movement of seabed drifters in San Francisco and the Gulf of the Farallones.[28] That report describes the movement of seabed drifters into San Francisco Bay from as far as 25 kilometers (15 miles) west of the Golden Gate. This is about the same distance that the surface phenomena of tidal outflow are clearly visible. The seabed drifter studies described in the 1970 USGS report were conducted during March, 1969, and therefore represent the same oceanographic conditions measured in connection with this study in February 1970.

Winter Season Dispersion Measurements. A full day of dispersion measurements was included in each of the February cruises. The locations, times and direction of movement of the dye patches for each cruise are shown on Figs. 4-12 and 4-13. Several transects were run through each dye patch, and dispersion coefficients were calculated for each transect using the procedure described previously. Values for k determined for the Gulf of the Farallones during February are presented in Table 4-2, and are shown graphically in Fig. 4-37 along with the coefficients for other seasons.

Summer Upwelling Season

Oceanographic conditions during the dry season, when upwelling was occurring, were measured during four days of continuous boatwork from June 16 through June 19, 1970. The primary purpose of the February cruises was the development of the general characteristics of the entire study area, with little effort expended toward the investigation of specific possible outfall locations. Evaluation of the data from the February cruises indicated that the primary purpose had been accomplished, and the June cruise was planned to give more detailed attention to two specific areas where outfall diffusers might be located.

The basic principles of outfall diffuser operation attach major importance to the depth of the discharge point. All other conditions being equal, the deepest discharge point is the superior one. With this factor in mind, a glance at the charts of the area outside the Golden Gate will indicate that the bar area is too shallow to be suitable for a major sewage discharge. Over an area of several square miles the water depth is less than 40 ft.

Table 4-2 Dispersion Coefficients in the Gulf of the Farallones, Winter Season

Dye drop time, PST	Time of measurement, PST	Axis of measurement[a]	Scale L, feet	Dispersion coefficient K, 10^4 ft^2/hr
February 3, 1970				
0759	0842	X	195.4	1.97
1010	1038	X	204.1	3.34
	1125	X	472.8	3.52
	1145	X	1002.9	61.30
	1058	Y	109.4	0.405
	1134	Z	3.8	0.00012
February 24, 1970				
0745	0808	X	153.8	2.09
	0832	X	643.8	30.32
	0947	X	3261.4	293.47
	0816	Y	92.5	0.384
	0854	Y	193.4	0.884
	0900	Z	7.4	0.0013
1145	1205	X	223.8	5.89
	1225	X	520.2	9.39
	1315	X	885.0	13.06
	1343	X	856.0	7.06
	1213	Y	113.7	0.771
	1236	Y	184.5	0.172
	1332	Y	535.4	10.0
	1240	Z	4.8	0.0004
	1352	Z	7.9	0.0004
1446	1523	X	103.7	0.456
	1555	X	156.2	0.261
	1656	X	580.8	12.13
	1536	Y	69.0	0.079
	1634	Y	184.5	0.917

[a] X = longitudinal Y = transverse Z = vertical

As a practical matter, then, the best sites for submarine disposal of sewage effluent lie either inside the bar or outside the bar. The June cruises were therefore planned to give particular attention to the oceanographic characteristics of two areas, one lying inside the bar and the other outside the bar to the south.

Two permanent stations (Figs. 4-19 and 4-20) were established for the June cruises. Station X was located in about 60 ft of water 7000 ft west of Point Lobos, and Station Y was set in 85 ft of water approximately 4.5 nautical miles southwest of Lake Merced. All physical oceanographic work during the June cruises was oriented around these two stations.

Work on June 17 (Fig. 4-19) was devoted primarily to dye dispersion studies. When convenient to the work schedule, temperature and dissolved oxygen profiles of the water mass were also obtained. A malfunction of the conductivity probe prevented the collection of salinity and density information on that date. Work on June 18 and 19 (Fig. 4-20) focused on definition of the vertical makeup of the water mass. The procedure involved first the measurement of temperature, dissolved oxygen, conductivity and current profiles at one of the permanent stations. While these measurements were in progress a buoy was released and its direction of drift noted. The research vessel then traveled approximately one mile in the direction of buoy movement and repeated the measurements. Finally, the vessel traveled two miles in the opposite direction, repeated the measurements, then moved on to the other permanent station. The result as shown on Fig. 4-20, was a pattern of physical measurements covering the general area both upcurrent and downcurrent from the permanent station.

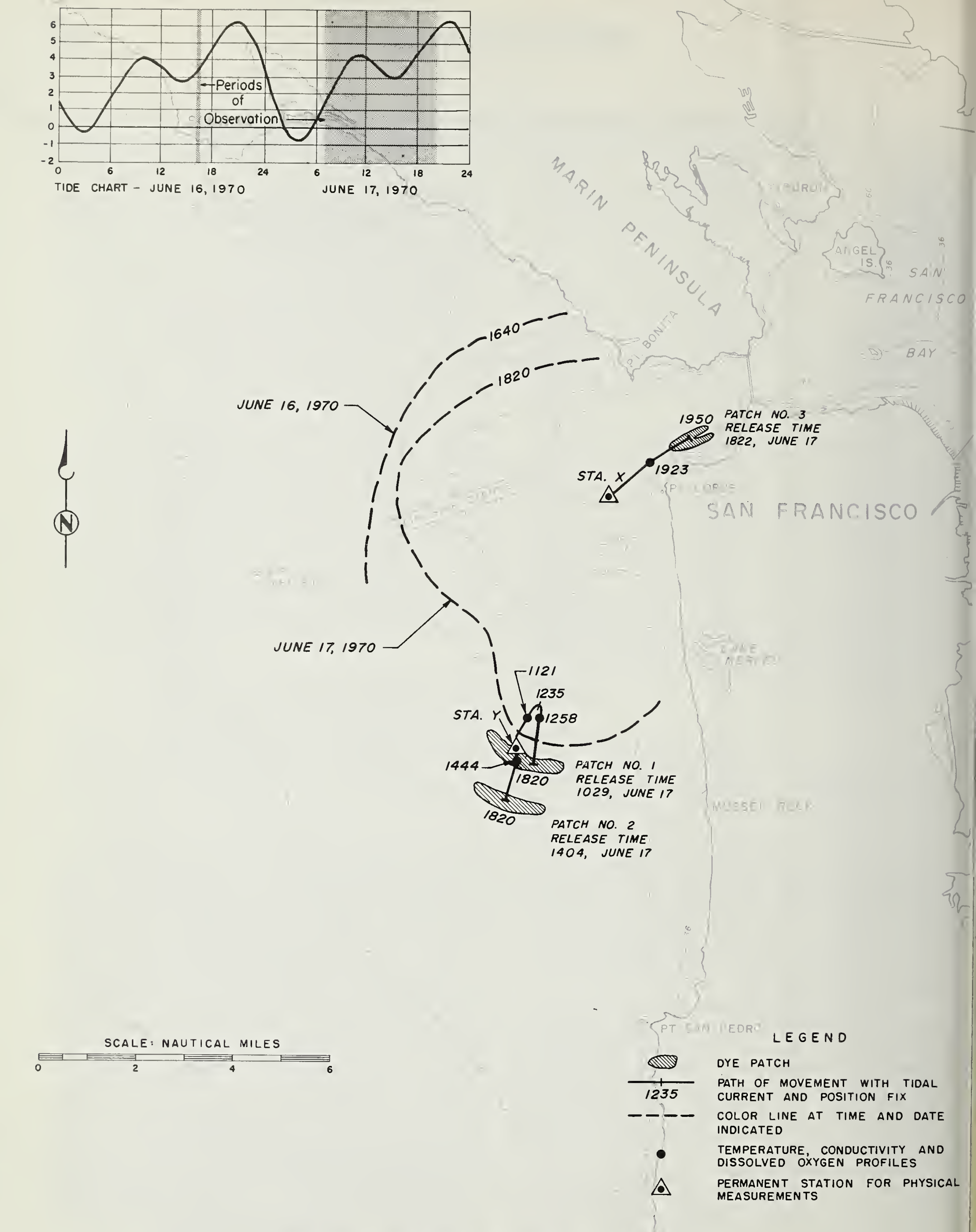


Fig. 4-19 **Mass Water Movement in the Gulf of the Farallones, June 16-17, 1970**

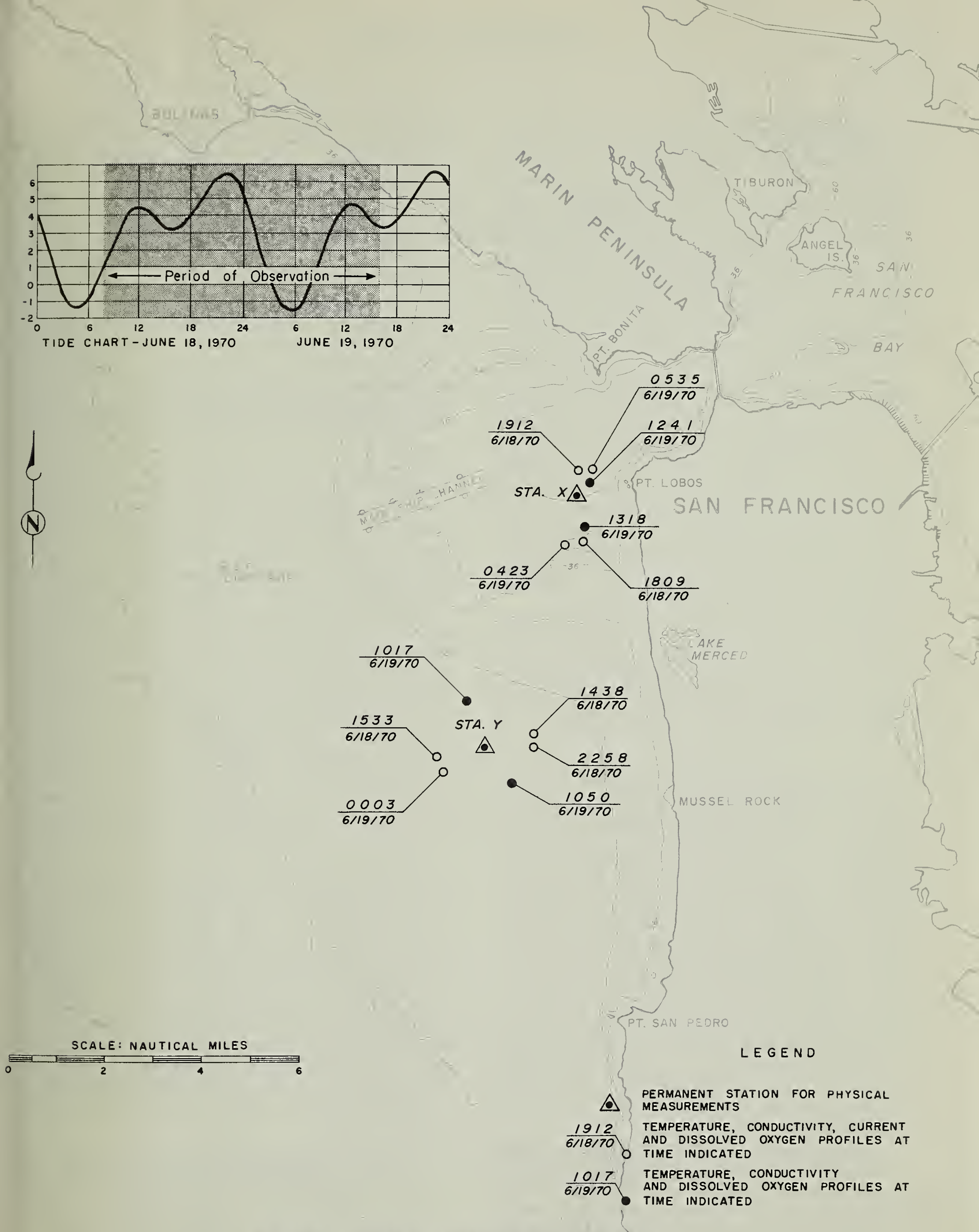


Fig. 4-20 Physical Oceanography in the Gulf of the Farallones, June, 1970

Summer Season Mass Water Movement. Aerial photographs of the color line at the edge of the outflowing bulb of bay water (Fig. 4-19) show the same pattern for June as had been observed previously. Movement was predominantly westward and southward. The color lines shown on Fig. 4-19 are for the short ebb, which explains in part the lesser distance of travel than in most previous observations. A second reason is that runoff of fresh water from the bay drainage area had diminished considerably from the January-February highs. Lower turbidity and poor conditions for observation prevented identification of the color line from the previous long ebb, but it may be assumed that the surface flow carried farther to the west and south than did ths short ebb.

It is interesting to note the surface movement of the dye patches dropped at Station Y. Net displacement of the first patch over an 8-hr period of observation was virtually zero, and the maximum movement over the short ebb was about 1.5 nautical miles. By comparison, the color line which passed Station X at the start of the ebb advanced 5 nautical miles to the south and an approximately equal distance to the west.

The third dye patch, dropped at Station X during the short flood, demonstrated the fact that at this time of year there is a definite surface flood current through the Golden Gate. This is a marked change from the winter season of high fresh water outflow.

Summer Season Physical-Chemical Characteristics. Graphs of salinity, temperature, density and dissolved oxygen plotted against water depth for the June cruises are presented in Volume 2, Data Supplement, for each of the observation points indicated on Figs. 4-19 and 4-20. Compared to the observations taken in February, several facts stand out clearly. The first is that the strong layering created by high fresh water outflow during the winter months had disappeared by June. The minimum surface salinity measured outside the Golden Gate in June was 30.8 ppt, compared to values as low as 10 ppt measured during February. Though there was still evidence of some reduction in surface salinity due to fresh water outflow, particularly on the ebbing tide, other factors showed a greater degree of vertical homogeneity inside the bar than outside the bar.

Stations south of the bar showed a marked thermocline at about 40 ft of depth, with temperatures below that level as much as 4 deg C colder than in the surface layers. The striking parallel between temperature and dissolved oxygen profiles indicates that the bottom layer was deep ocean water, cold and low in dissolved oxygen, brought to the area by upwelling. The existence of the bottom layer is demonstrated by the plots of dissolved oxygen versus time and depth for a 24-hr period (Figs. 4-21 and 4-22). As shown in Fig. 4-22, dissolved oxygen values for Station Y and vicinity at depths less than 30 ft are typical for surface waters of the ocean in this area, averaging about 8 mg/l. Below 50 ft, however, dissolved oxygen dropped off to an average of around 4 mg/l. Inside the bar, at Station X and vicinity, dissolved oxygen values averaged about 6.5 mg/l throughout the entire depth. The plots of dissolved oxygen versus time (Fig. 4-21) also show the layering due to upwelling which existed south of the bar.

The depth from the surface to the layer of upwelled deep ocean water can be expected to vary depending on the strength of the winds which cause the phenomenon of upwelling to occur. During the June cruises the depth was consistently about 40 ft, but at other times it may reach the surface or be absent altogether. The incidence of surface upwelling is lower south of the Golden Gate than to the north, however. This fact is indicated by records of surface temperatures for the area and by the incidence of fog, which is much greater north of the Golden Gate than south. In fact, the Point Reyes area is reported to be the foggiest place in the United States.

Water clarity, as would be expected from the evidence of mass water movement, is greater south of the bar than inside the bar. Secchi readings (Fig. 4-23) inside the bar over three days of observation ranged from 5 to 11 ft, with a median of about 8 ft. South of the bar, the range was from 6.5 ft to 21 ft, with a median of about 16 ft. The lower values south of the bar were taken in the morning hours, and were the first observations after the long ebb. Based on previous evidence of mass water movement, it may be assumed that a surface layer of higher turbidity from San Francisco Bay flowed southward past the southern observation area during the early morning hours. Morning haze and overcast prevented documentation of the color line movement from the long ebb, and by afternoon, when the higher Secchi disc measurements were recorded, the color line was no longer visible.

Summer Season Currents. Data on currents in the Gulf of the Farallones during the season of upwelling were obtained from three principal sources. The first was USC&GS current records

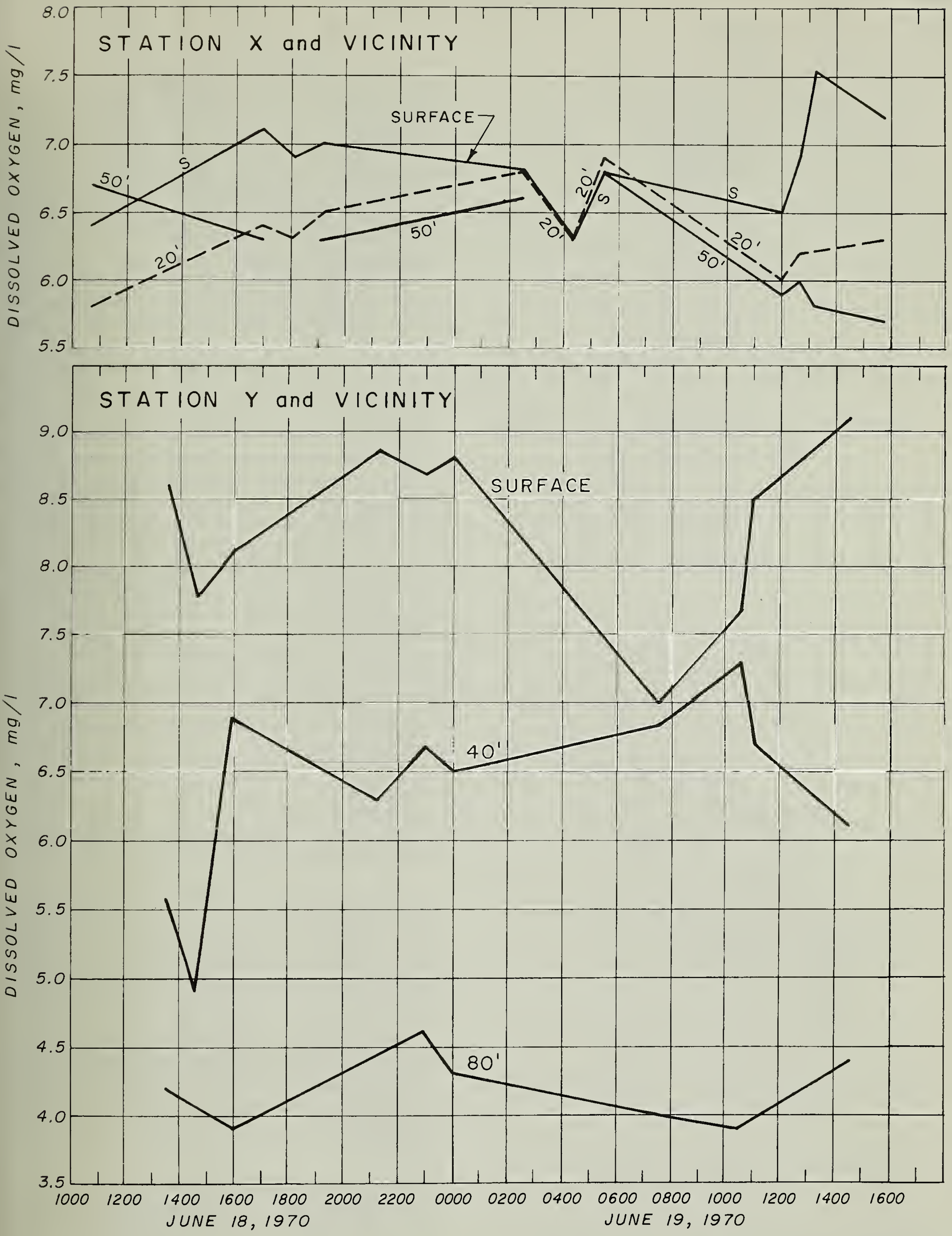
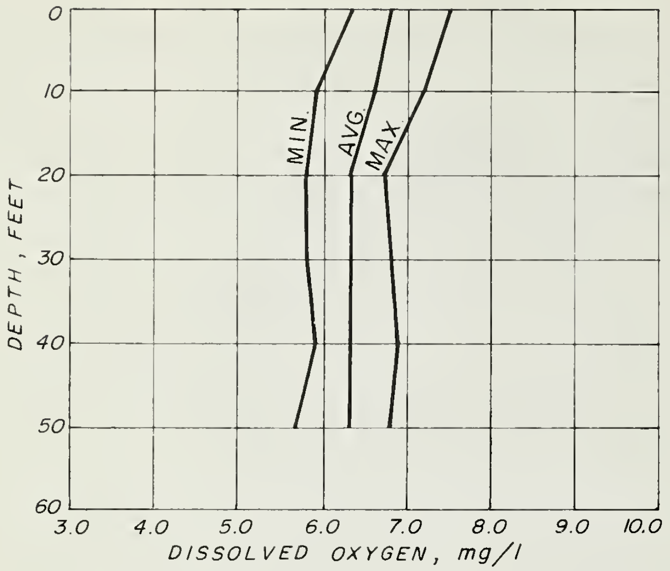
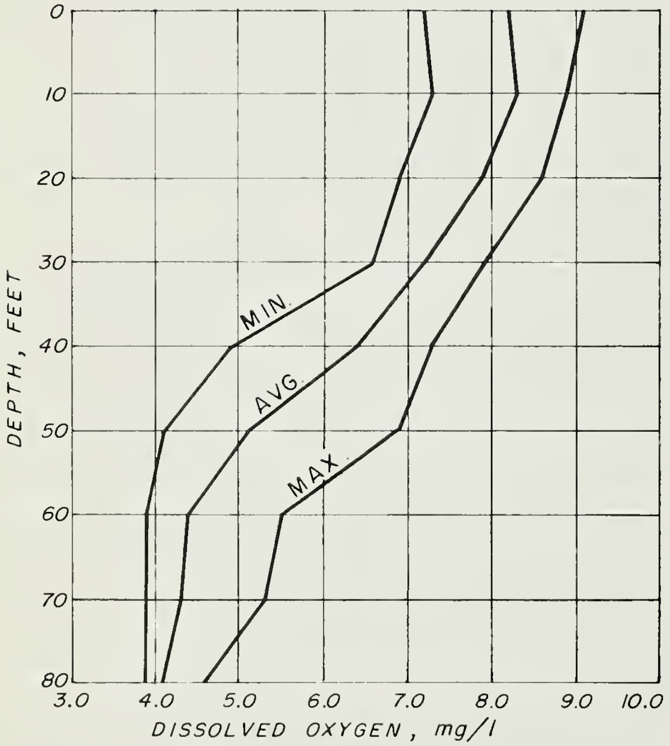


Fig. 4-21 Dissolved Oxygen vs Time, Gulf of the Farallones, June, 1970



STATION X and VICINITY, JUNE 18-19, 1970



STATION Y and VICINITY, JUNE 18-19, 1970

Fig. 4-22 Dissolved Oxygen vs Depth, Gulf of the Farallones, June, 1970

taken during July and early August 1953, at the stations shown on Fig. 4-4. Data for Stations 61 and 74 are presented in Volume 2, Data Supplement, in the form of advective flow diagrams. Advective flow diagrams are presented for all depths for which data were taken, and cover two complete tidal cycles representing the greatest difference in tidal conditions which occurred during the period of measurement.

The second source of information is the current profiles taken during the oceanographic cruises associated with this study, on June 17, 18 and 19, 1970. This information is presented in the Data Supplement in tabular form and in the form of current vectors plotted for 10-ft depth intervals.

The third source of data is the float studies conducted by Brown and Caldwell in August, 1962 as a part of predesign investigations for the North San Mateo County Sanitation District submarine outfall west of Lake Merced.[29] Each float consisted of a set of fiberglas vanes suspended about five ft below the surface and buoyed by a surface float. The floats were dropped in pairs and their movement was followed by a boat which took periodic fixes on the position. Floats dropped less than 1800 ft offshore moved quite rapidly toward the beach, while floats released from 1800 to 2500 ft offshore traveled almost precisely parallel to the shoreline. Floats released on an ebbing tide traveled southerly at speeds of 0.26 K to 0.88 K. One float was retrieved at Seal Rocks, four miles north of the release point.

A study of all of the current data collected for the Gulf of the Farallones during the summer months indicates several interesting facts:

1. The massive difference between surface and subsurface currents, which characterized the winter period, has largely disappeared by June. There is still a recognizable difference as indicated both by the current vectors and displacement diagrams.

2. All current measurements show the predominating influence of the tidal ebb and flow from San Francisco Bay. As would be expected, the stations farthest from the Golden Gate have the weakest currents and show the least tidal influence.

3. Advective flow diagrams for Stations 68 and 69 demonstrate the predominant southeasterly flow through Bonita Channel, which supplies a major portion of the volume for the flooding tidal prism.

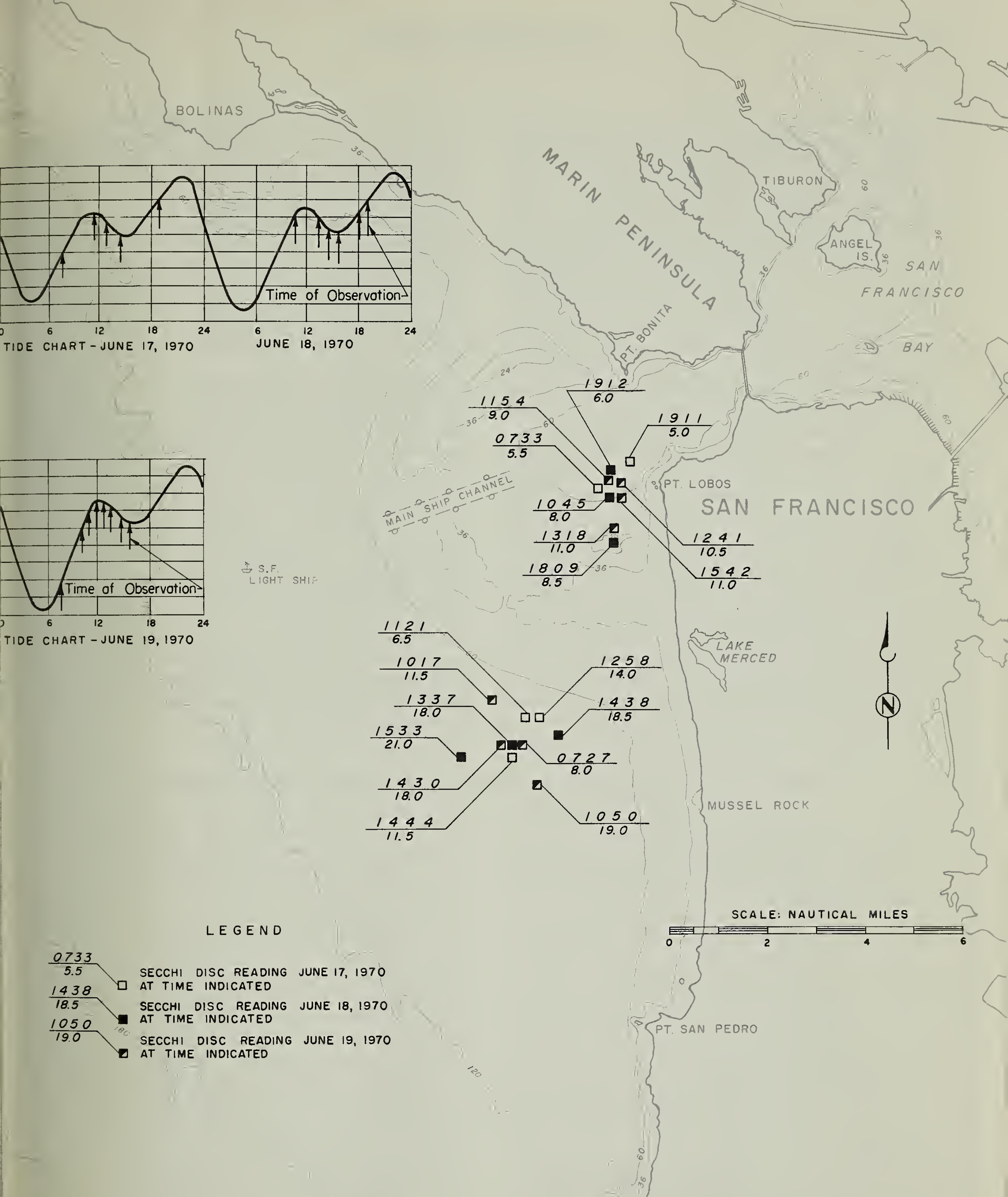


Fig. 4-23 **Water Transparency in the Gulf of the Farallones, June, 1970**

4. At Station 70 north of the north bar the currents are weaker and show a predominant westerly flow, especially at mid-depth. The advective flow diagrams indicate the presence of an eddy north of the bar which carries water eastward to the northern end of Bonita Channel.

5. Advective flow diagrams for Stations 71, 72 and 73 show the strong seaward displacement to the west and southwest which was observed repeatedly in photographs of moving color lines.

6. Station 74, located over the south bar about 4000 ft offshore, showed the same current pattern parallel to shore which was observed in float studies west of Lake Merced. Net advection at Station 74 was slightly to the south on the surface and slightly northerly at mid-depth.

7. Stations 64, 65 and 66, at the mouth of the Golden Gate, predictably showed the highest current values of any stations in the Gulf of the Farallones. Average values are in excess of 1 K and maximum values are more than 3 K. The mass displacement vectors for the three stations are quite variable, probably reflecting the strong eddying which occurs around the headlands. The general trend, however, is a seaward movement on the surface and a bayward movement at mid-depth and below. The same trend is shown in the current vector plots for Station X and vicinity, inside the south bar, measured on June 17, 18 and 19 of 1970.

Summer Season Dispersion Measurements. The cruise on June 17 was devoted to measurement of dispersion coefficients both inside and outside the bar. The locations, times and direction of movement of the dye patches are shown on Fig. 4-19, and the calculated dispersion coefficients are presented in Table 4-3. The dispersion coefficients shown in the table, together with all other coefficients determined for the Gulf of the Farallones in the course of the study, are shown in Fig. 4-37. The results of the dispersion studies are evaluated and discussed later in this chapter.

Summer Season Surface Drift. The first surface drift measurements conducted in connection with this study were carried out during the period from June 16 to June 23, 1970. Cardboard milk bottle caps were dropped at three stations, identified as X, Y and Z, following the procedure described previously. Stations X and Y were the same as those established for physical oceanographic measurements (Fig. 4-20). Station Z was in the Central Bay between Blossom Rock and Alcatraz Island. Three drops, consisting of 1500 caps each, were made at each of the three stations. Drops were made as close to the time of tidal nodes as the other items in the oceanographic work program would permit, and each batch of caps was spread over a distance of about 600 ft to simulate initial dispersion of a sewage field.

Table 4-3 Dispersion Coefficients in the Gulf of the Farallones, Summer Season

Dye drop time, PDST	Time of measurement PDST	Axis of measurement[a]	Scale L, feet	Dispersion coefficient K, 10^4 ft^2/hr
June 17, 1970				
1029	1052	X	206.4	4.25
	1108	X	438.5	6.14
	1156	X	1003.5	30.70
	1639	X	1997.5	10.68
	1229	Y	215.0	0.886
	1714	Y	438.7	0.270
	1132	Z	13.7	0.00698
1404	1530	X	795.6	20.70
	1430	Y	168.1	2.31
	1436	Y	239.2	0.871
	1559	Y	709.5	10.08
	1456	Z	11.9	0.0061
1822	1849	X	217.8	4.06
	1940	X	752.8	16.26
	1903	Y	120.4	0.623
	1922	Z	8.0	0.002

[a] X = longitudinal Y transverse Z vertical.

Caps were dropped at station Z on June 16, and at stations X and Y on June 18-19. All of the shoreline areas shown on Figs. 4-24 and 4-25 were searched on June 20 and again on June 23 to recover bottle caps which had drifted ashore. Each bottle cap was identified by pattern to determine location of release. The results in terms of caps recovered and location of recovery are presented in Figs. 4-24 and 4-25.

Perhaps the two most interesting facts to emerge from the data collected are the following: (1) of a total of 13,500 caps dropped at all three stations not a single cap was recovered inside the Golden Gate, and (2) of the 4500 caps dropped at Station Z in the Central Bay not a single cap was recovered at any location. A lower percentage recovery would normally be expected within the bay because the ratio of shoreline searched to total shoreline was lower than along the ocean beaches. However, the areas selected for investigation within the bay were those most sensitive esthetically to the accumulation of floatable materials, and the fact that not a single cap was recovered at any point is significant. Since the regulation of floatable material is primarily for esthetic reasons, it is fair to state that floatables which cannot be found do not constitute a violation of receiving water criteria. The failure to recover any caps from those dropped in the Central Bay is presumed to be evidence that the caps were carried so far seaward by the ebbing tide that they were either entrained in the major oceanic current system or simply could not be moved ashore by wind action in the week that elapsed before the final search was made.

Some significant differences in the behavior of bottle caps released at Stations X and Y are also apparent from the analysis of the data. One such difference is in the percentage of caps recovered at the two stations. For Station X, which lies just over a mile offshore, a total of 16 percent of the caps dropped were recovered. For Station Y, which lies four miles offshore, 25 percent of the caps dropped were recovered. A second difference is in the area over which the recovered caps were distributed. As might be expected, the caps recovered from Station Y, the southern station, were confined to the coastline south of the Golden Gate. The heaviest concentration was recovered from the San Mateo County coast in the vicinity of Thorton State Beach. The caps dropped at Station Y were recovered all the way from Stinson Beach to Point San Pedro, with the heaviest concentration located in the Lands End-Bakers Beach area.

The results of the surface drift measurements for Stations X and Y are consistent with the information developed on mass water movement. Caps dropped at Station X were more likely to be swept along in the strong westward-flowing tidal ebb through the Golden Gate and dispersed in the oceanic current system. This accounts for the smaller percentage recovery and for the wider dispersion of recovered units despite the location of Station X closer to shore.

The cap recovery operation was extended northward and southward along the accessible ocean beaches until a beach was found which produced no bottle caps. This was assumed to be the limit of the geographical spread, and the recovery operation was discontinued at that point. No caps from any drop in June were recovered north of Stinson Beach or south of Rockaway Beach.

Other Surface Drift Studies. Two other surface drift studies using the same measurement technique have been conducted in the Gulf of the Farallones in recent years. The first was conducted by Brown and Caldwell in 1962 in connection with the design of a submarine outfall for North San Mateo County Sanitation District.[29] Bottle caps were released at eight locations from 700 to 2300 ft offshore immediately west of Lake Merced on July 20 and 26 (Table 4-4). As shown in the table, the shoreward velocity ranged from 11 to 37 fpm, and substantially all of the caps released arrived at the beach in less than three hours. The caps were distributed along the beach for a distance of 7000 ft north of the release point and 3500 ft south of the release point.

The second independent study of surface drift was conducted in the Bolinas area in August, 1966 in connection with the Marin County Sewerage Study.[25] Two releases of 500 caps each were made 2000 ft offshore in the Bolinas area. Of the caps dropped offshore of Rocky Point, 83 percent were recovered from the adjacent beaches, most within a period of four hours. Of the 500 caps dropped 2000 ft offshore of Bolinas Mesa, where a prevailing northerly current had been defined running parallel to the coastline, 30 percent were recovered. The average shoreward velocity in the former case was about 10 fpm. In the latter case the shoreward velocity was not well documented, but was less than 7 fpm.

Fall Season After Upwelling

By September upwelling has usually subsided, but the northward-flowing Davidson current has not yet begun. This period, which may

Table 4-4 Surface Drift, North San Mateo County Coast, July, 1962

Date	Release data[a]		Recovery data		
	Distance offshore, feet	Time, PDST	Time to reach shore, minutes	Shoreward velocity, feet per minute	Percent recovered
July 20	1,450	1009	41	37	99
	2,300	1027	98	24	89
	1,300	1505	115[b]	11	97
	1,800	1515	165[b]	11	92
July 26	800	1010	60	13	99
	1,800	1015	105	17	96
	700	1454	33	21	99
	2,000	1502	74	27	86

[a] Each release consisted of 500 cardboard milk bottle caps.

[b] Approximate.

stretch from late August to November, is as previously noted sometimes referred to as the Oceanic Season. Several factors combine to indicate that from the standpoint of sewage effluent disposal in the Gulf of the Farallones this is probably the most critical period of the year. Principal among these factors are:

1. Climatic conditions are most suited to recreational use of the ocean waters. Air and water temperatures are at the annual high and the strong westerly winds of the summer season have subsided.
2. Water clarity is greatest at this season of the year, which means that the chances of esthetic objections to discoloration by a sewage field are more likely to occur during the fall season.
3. Fresh water outflow from the San Francisco Bay system is at about the annual low, which in turn has two effects:
    a. Density gradients within the zone of influence of the bay outflow are at their annual low values.
    b. Seaward displacement of the surface layer, which is greatest at maximum fresh water outflow, will be at a minimum.

The fall cruises were conducted during the week of October 5-11 and were completed before the first rain of the fall season.

Fall Season Mass Water Movement. On September 8, 1970 a full day was spent in aerial observation of the movement of water masses in the Gulf of the Farallones. Results of the observations are presented in Fig. 4-26. As indicated on the tide chart, the morning ebb on September 8 had an amplitude of only 0.3 ft, which represents the minimum ebb condition for this section of the California coast. Since the minimum ebb was observed during the fall season, it may be considered representative of the minimum outflow condition from San Francisco Bay. Despite the fact that the ebb amplitude was only 0.3 ft, ebb currents persisted for over four hrs, and the turbidity bulb moved more than six miles past the Golden Gate headlands.

As shown in Fig. 4-26, the turbidity line from the long ebb on the evening of September 7 was faintly but distinctly visible just east of the San Francisco Lightship. Its position remained virtually constant throughout the daylight hours of September 8.

The turbidity bulb from the short ebb moved westward and southward in a manner which has been typical for virtually every observation. It differed only in magnitude of the phenomenon, which was the smallest observed during the course of the study. As the flood got underway following the short ebb, the moving color lines demonstrated again the phenomenon which has been observed repeatedly in all seasons and documented by current and salinity observations. The outer boundary of the turbidity bulb remained practically unchanged throughout the flood cycle, while clear ocean water could be observed pouring around the headlands from the north and south.

On this particular date, the nearshore surface current west of Lake Merced remained northward parallel to the shore throughout the entire ebb cycle. This fact was documented by observation of the surface plume from the North San Mateo County Sanitation District outfall, about 2300 ft offshore, and the effect of the northerly current is evidenced by the fact that the nearshore color lines never advanced to the south past Golden Gate Park.

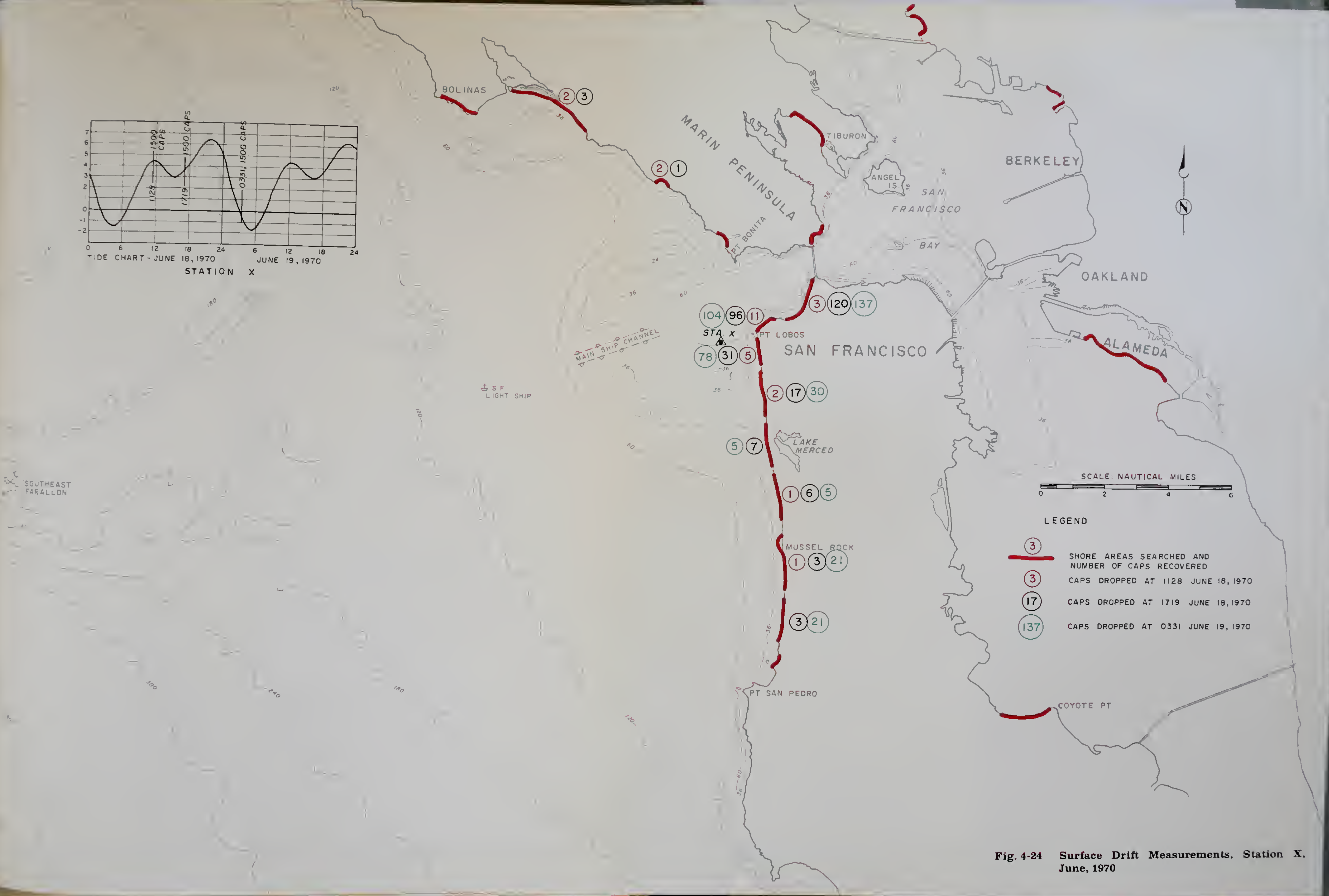


Fig. 4-24 **Surface Drift Measurements, Station X, June, 1970**

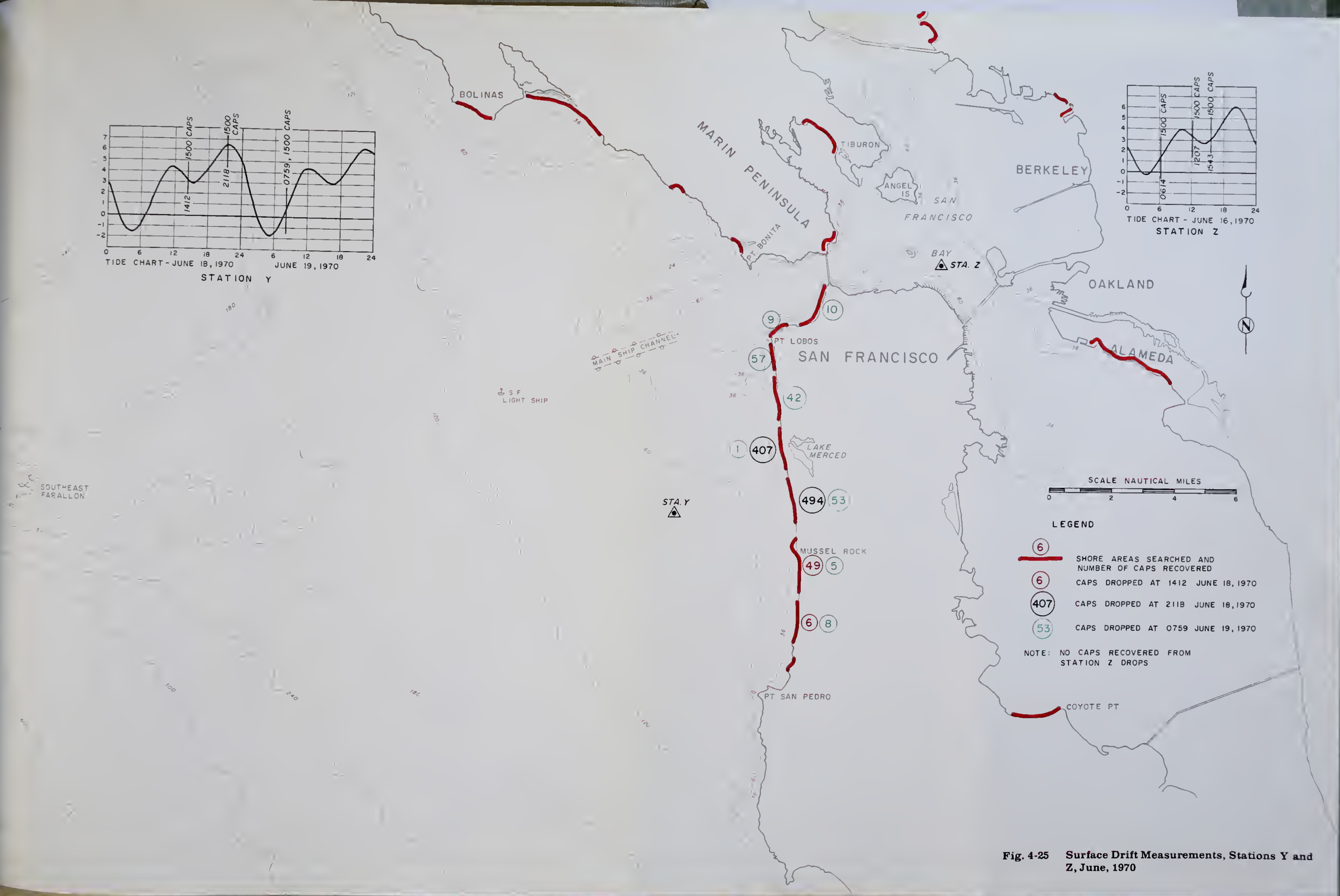


Fig. 4-25 Surface Drift Measurements, Stations Y and Z, June, 1970

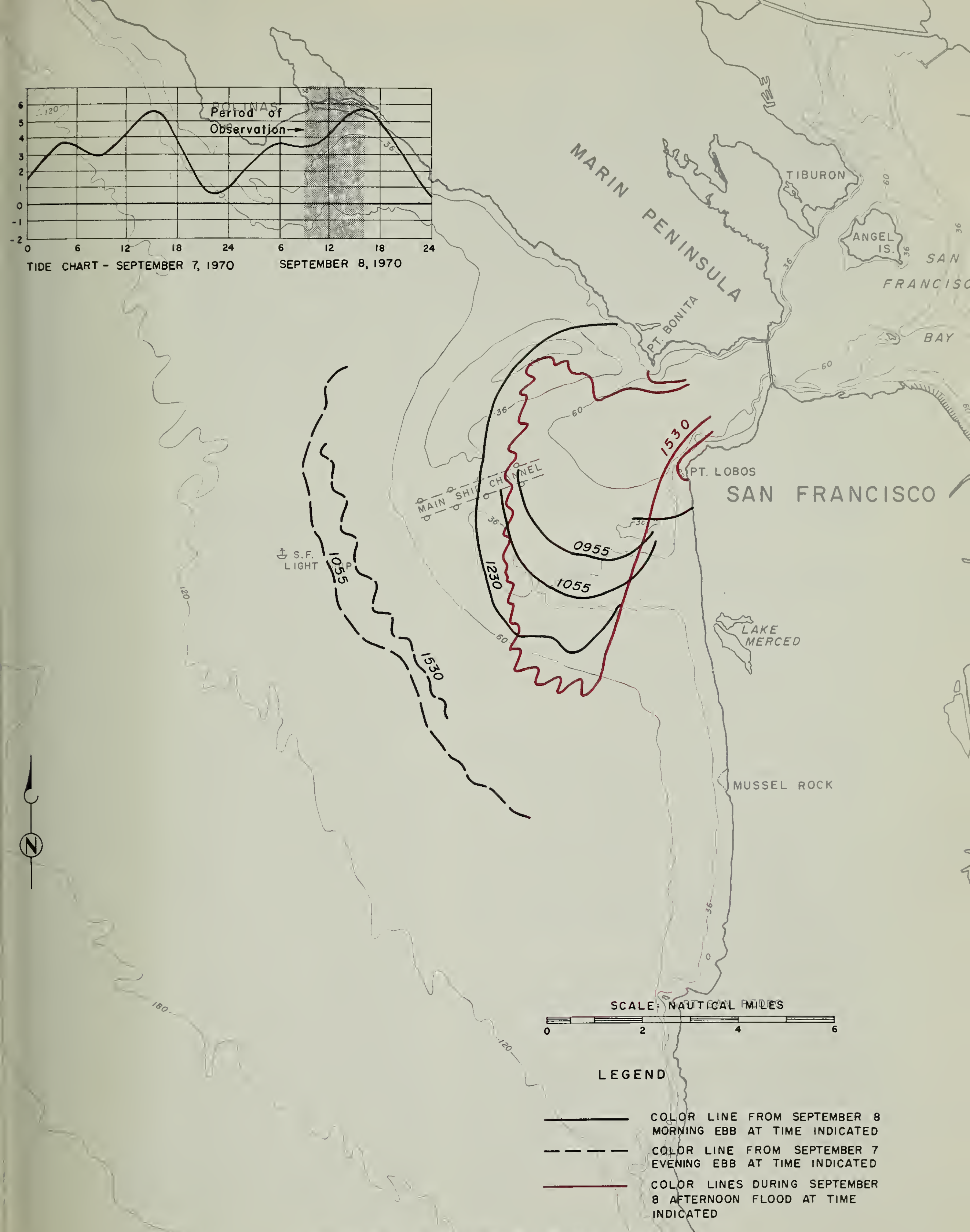


Fig. 4-26 Mass Water Movement in the Gulf of the Farallones, September, 1970

The detailed information on surface mass water movement presented in Fig. 4-26 was confirmed by two observations of the turbidity bulb on October 6 (Fig. 4-27). The observed tide on that date was also a short ebb, but of slightly greater amplitude than that of September 8. Movement to the west was about the same on both dates, but the turbidity bulb moved farther to the south on October 6. The phenomenon of clear ocean water flooding tiward the Golden Gate from both north and south nearshore was observed on both dates.

Fall Season Physical-Chemical Characteristics. By the start of the investigations of the fall season it was felt that sufficient information had been obtained on the general oceanography of the study area to warrant more detailed investigation of specific points where outfall diffusers might be located and where information accumulated to that time was not adequate. Accordingly, two stations were selected for investigation over a complete tidal cycle. (Fig. 4-27).

Station A was located in 45 ft of water approximately 5500 ft offshore of the southern edge of Golden Gate Park. This is an area where the current velocities are less than in the deeper portion of the main channel to the north. It also represents approximately the shallowest depth at which one might construct a satisfactory outfall diffuser for a relatively small flow.

Station B was located in 90 ft of water six nautical miles from Point Lobos. This location is outside the bar to the west, and was selected for comparison with Station Y, outside the bar to the south, which was investigated on the June cruises.

Each station was occupied by an anchored boat for a full 25-hr tidal cycle, during which hourly profiles were measured for current, temperature, dissolved oxygen and salinity. Profiles of temperature, dissolved oxygen, salinity and density, plotted against depth, are included in Volume 2, Data Supplement.

Of particular interest in submarine outfall design are the characteristics of dissolved oxygen and water density. Information on dissolved oxygen versus time and dissolved oxygen versus depth for both Stations A and B is presented in Figs. 4-28, 4-29 and 4-30. These figures show the same relationships between the stations inside and outside the bar as were revealed by Figs. 4-21 and 4-22 from the June cruises. Station A, inside the bar, shows evidence of more complete mixing, with only moderate variation in dissolved oxygen with time and depth. The maximum recorded value was 8.3 mg/l and the minimum value 6.3 mg/l.

Station B, outside the bar, showed marked variation in dissolved oxygen with both time and depth. Surface dissolved oxygen was high during the daylight hours on October 10 due to phytoplankton activity, but dropped sharply at about 1600 hours when the morning ebb tide moved a surface layer of lower salinity water past the station (Fig. 4-32). The relationship between dissolved oxygen and phytoplankton is discussed further in Chapter 5. It is interesting to note that the dissolved oxygen values at 15 ft depth were consistently higher than the surface values. Below 70 ft depth, dissolved oxygen was virtually constant at 5.4 to 5.8 mg/l. It will be noted that these minimum values are significantly higher then the 4 mg/l recorded at a similar depth during June.

Water clarity at Stations A and B is also plotted in Figs. 4-28 and 4-29 in terms of Secchi disc readings. For Station A values ranged from 12 to 17 ft, while for Station B values ranged from 16 to 24.5 ft. The range of values both inside and outside the bar was the greatest recorded during the study, confirming the premise that water clarity during the fall season is at the annual high. However, values for water clarity can vary appreciably from day to day. As shown on Fig. 4-27, Secchi disc readings of 8 and 9 were observed near Station A on October 5, and on the same date a value of 12 ft was observed near Station B.

In Figs. 4-31 and 4-32 water density is plotted against time and depth for Stations A and B. These data are consistent with the composite picture of mass water movement developed from all other information. In Fig. 4-31, high density new water may be seen moving past Station A during the flood tide on October 7. Below 30 ft depth the density approaches the value for ocean water. The long ebb on the evening of October 7 moved low density water past the station in a broad front extending from surface to bottom. The short ebb on October 8, on the other hand, moved low density water past the station only in a surface layer with a depth of 15 to 20 ft.

The density plot for Station B is equally interesting (Fig. 4-32). Below a depth of 45 ft the water is near oceanic density at all times, with little evidence of tidal fluctuation. In the surface layer above 30 ft, on the other hand, there is clear evidence that a low salinity layer moves past the station with each strongly ebbing tide. In relating density at Station B to tidal action it must be remembered that slack water at the Golden Gate

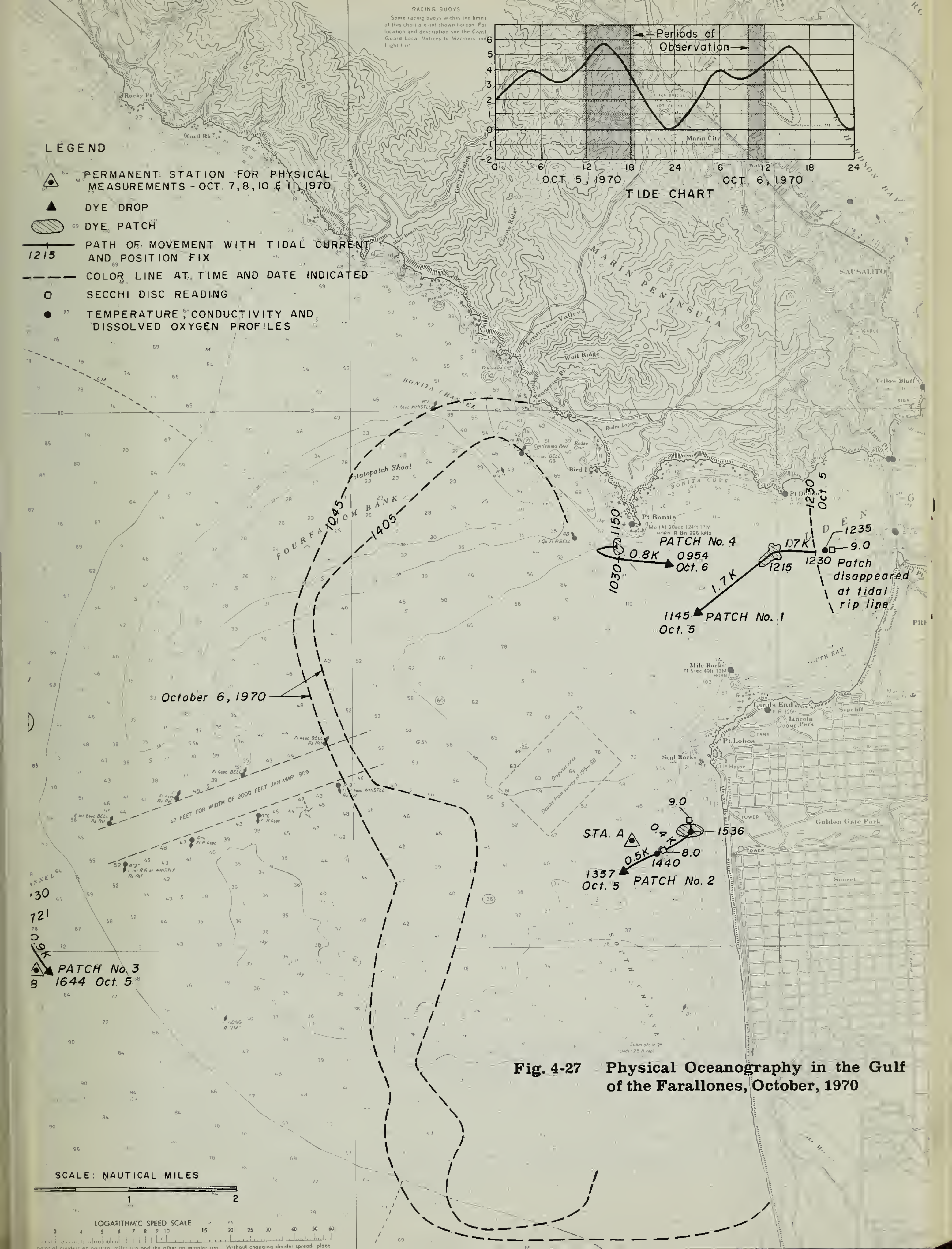


Fig. 4-27 Physical Oceanography in the Gulf of the Farallones, October, 1970

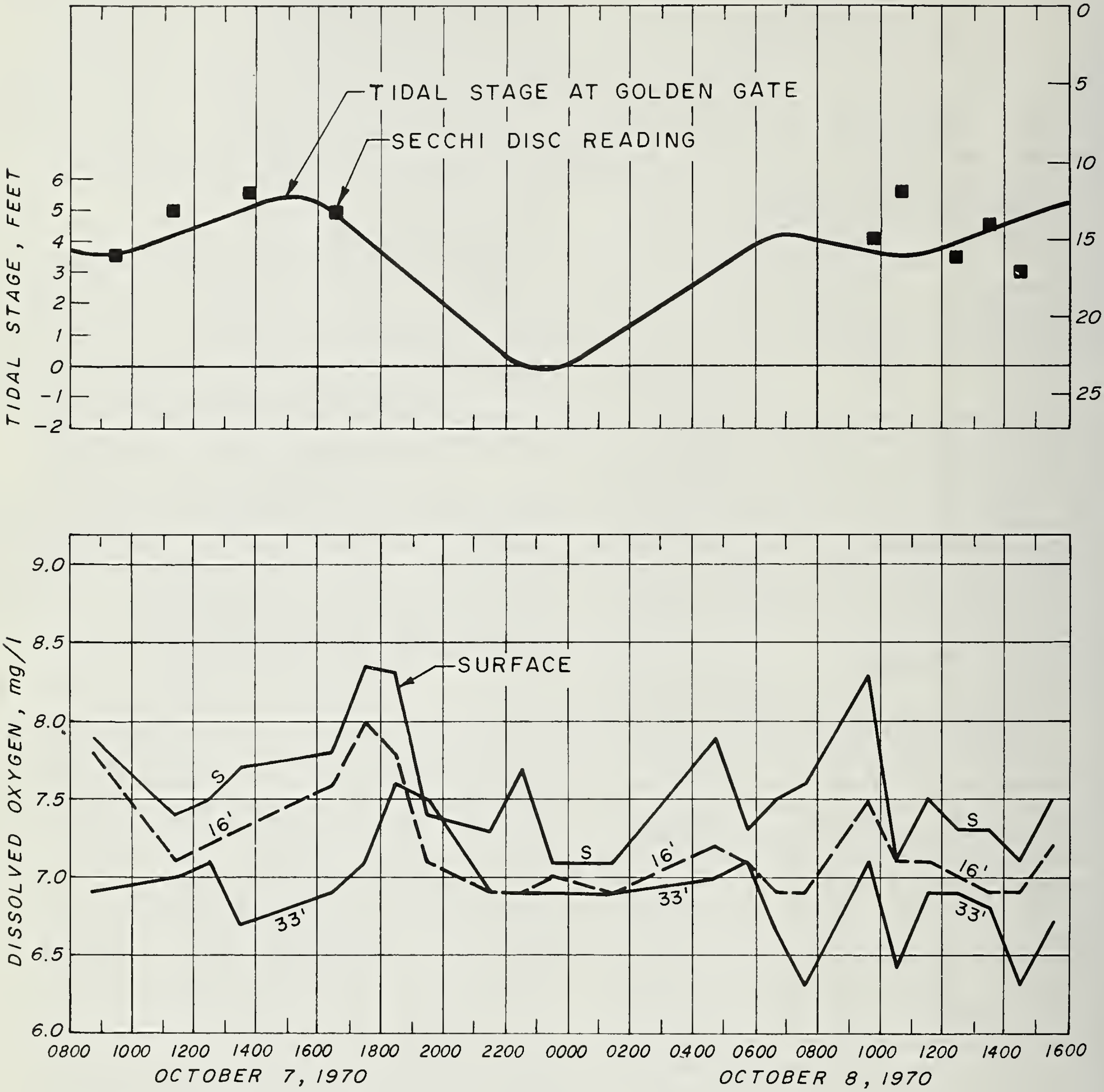


Fig. 4-28 Dissolved Oxygen and Water Clarity vs Time, Station A, Gulf of the Farallones, October, 1970

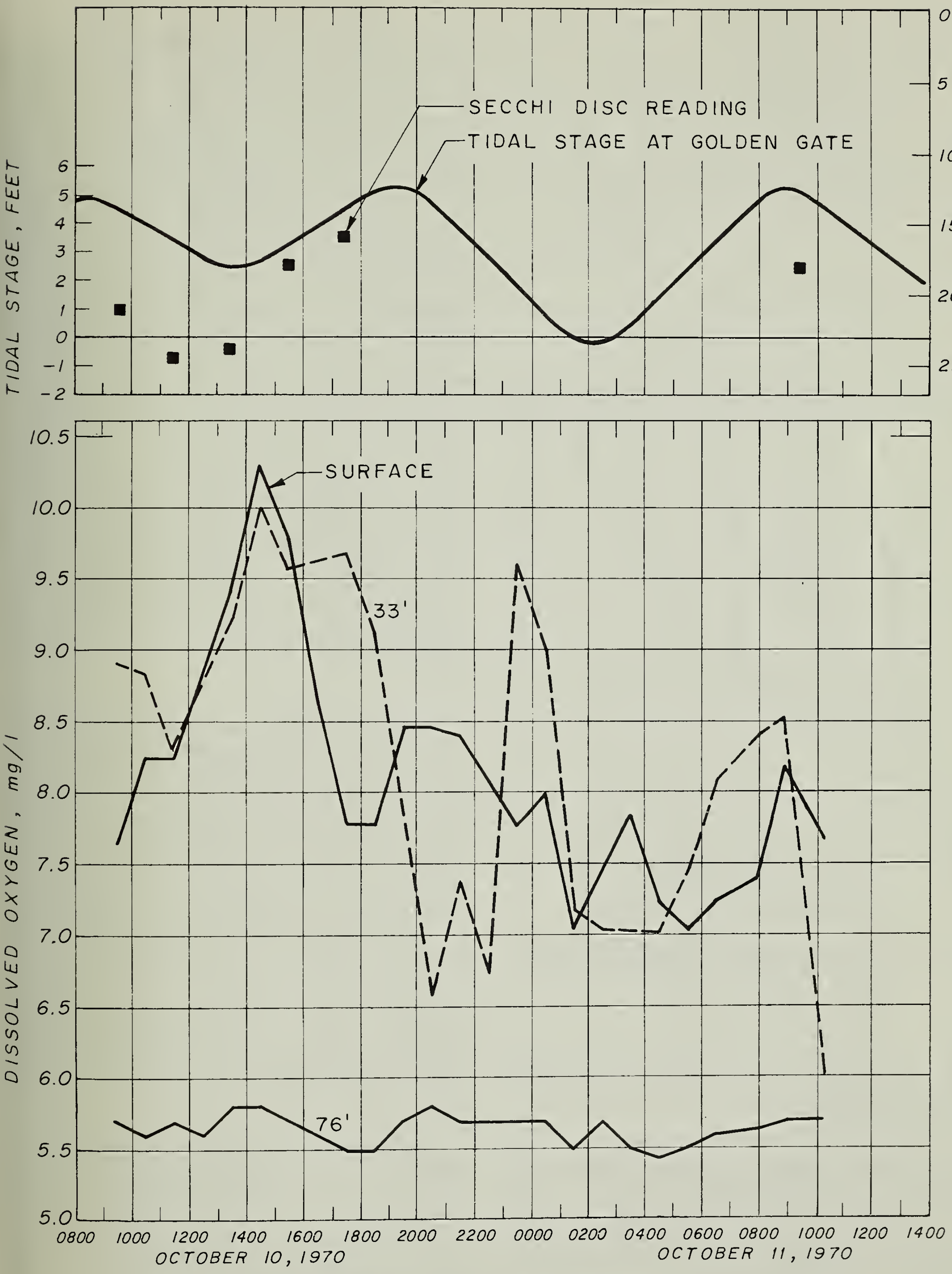
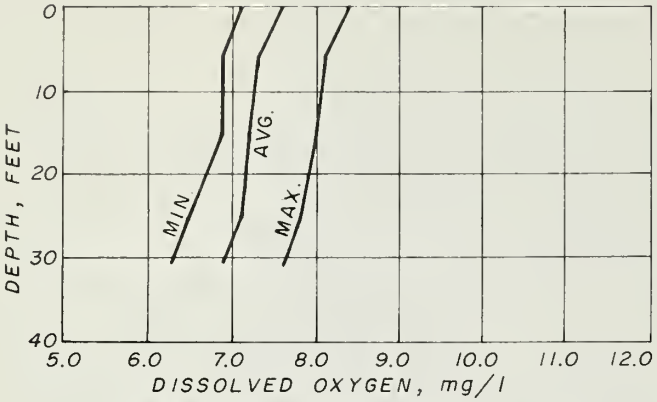
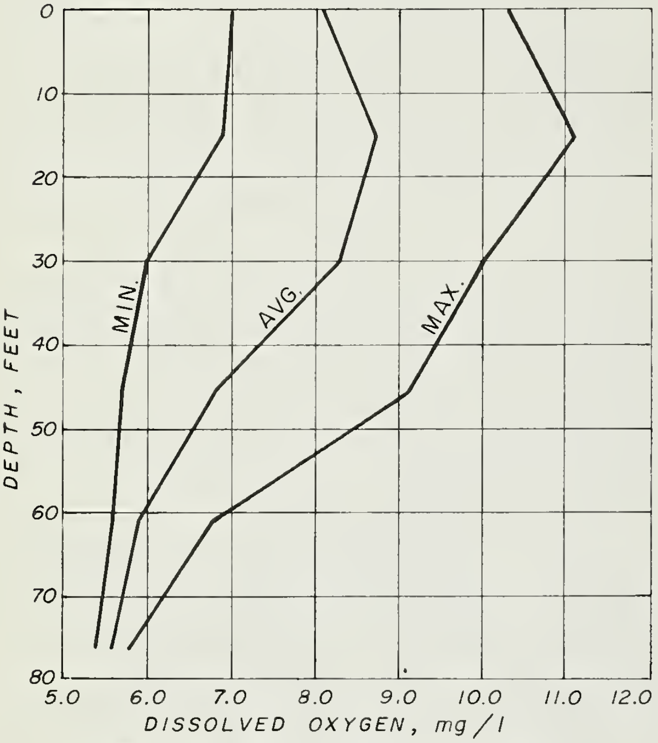


Fig. 4-29 **Dissolved Oxygen and Water Clarity vs Time, Station B, Gulf of the Farallones, October, 1970**



STATION A, OCTOBER 7-8, 1970



STATION B, OCTOBER 10-11, 1970

Fig. 4-30 Dissolved Oxygen vs Depth, Stations A & B, Gulf of the Farallones, October, 1970

occurs about an hour after the tidal node, and that Station B is located six miles west of the mouth of the Golden Gate.

Fall Season Currents. Current profiles were recorded at hourly intervals for a full 25-hr tidal cycle at Stations A and B. The results of these observations are presented in Volume 2, Data Supplement, in tabular form and as advective flow diagrams at three depths.

The surface advective flow diagram for Station A shows an approximate balance between flood to the northeast and ebb to the southwest, and rather surprisingly shows a pronounced shoreward displacement. This is the first time that a shoreward current vector in this area has been recorded, but its presence at this time of year is confirmed by the shoreward movement of a dye patch dropped near Station A on October 5, 1970 (Fig. 4-27). It is quite likely that the currents within about 2000 ft of the beach were parallel to the shore as has been previously recorded, but this could not be confirmed for the October measurements. The advective flow diagram for 33 ft of depth at Station A showed a definite flood predominance.

Currents at Station B were small in magnitude compared with currents inside the bar. The average velocity was about 0.6 K at the surface and 0.4 K at depths below 30 ft. Currents at 80 ft depth were even less, with many measurements below the minimum value of 0.2 K which the meter would record. The conclusion from current measurements, which is supported by information on salinity and dissolved oxygen, is that very little water movement takes place near the bottom at Station B.

Fall Season Dispersion Coefficients. Dye dispersion studies were conducted on October 5 and 6 at the points shown on Fig. 4-27. Patch No. 1, dropped at the mouth of the Golden Gate at about maximum flood current, represented an attempt to track a dye patch through the Golden Gate and measure its dispersion by the time it reached the bay. However, before it had traveled more than half way through the gate it met a developing ebb line and was forced below the surface. Attempts to locate the submerged patch by vertical profiling were ineffective. A final attempt was made on the following day by dropping Patch No. 4 earlier in the flood cycle. However, this patch caught the tail end of the ebb current and had not yet entered the gate by the time the work had to be abandoned because of rough seas.

Patch No. 3 was dropped at Station B, to the west of the bar, on October 5. Poor visibility and distance from shore prevented accurate tracking of the patch by shore fixes. Subsequent information on patch movement was obtained by aerial observation and is consistent with current measurements at Station B. In any event, direction

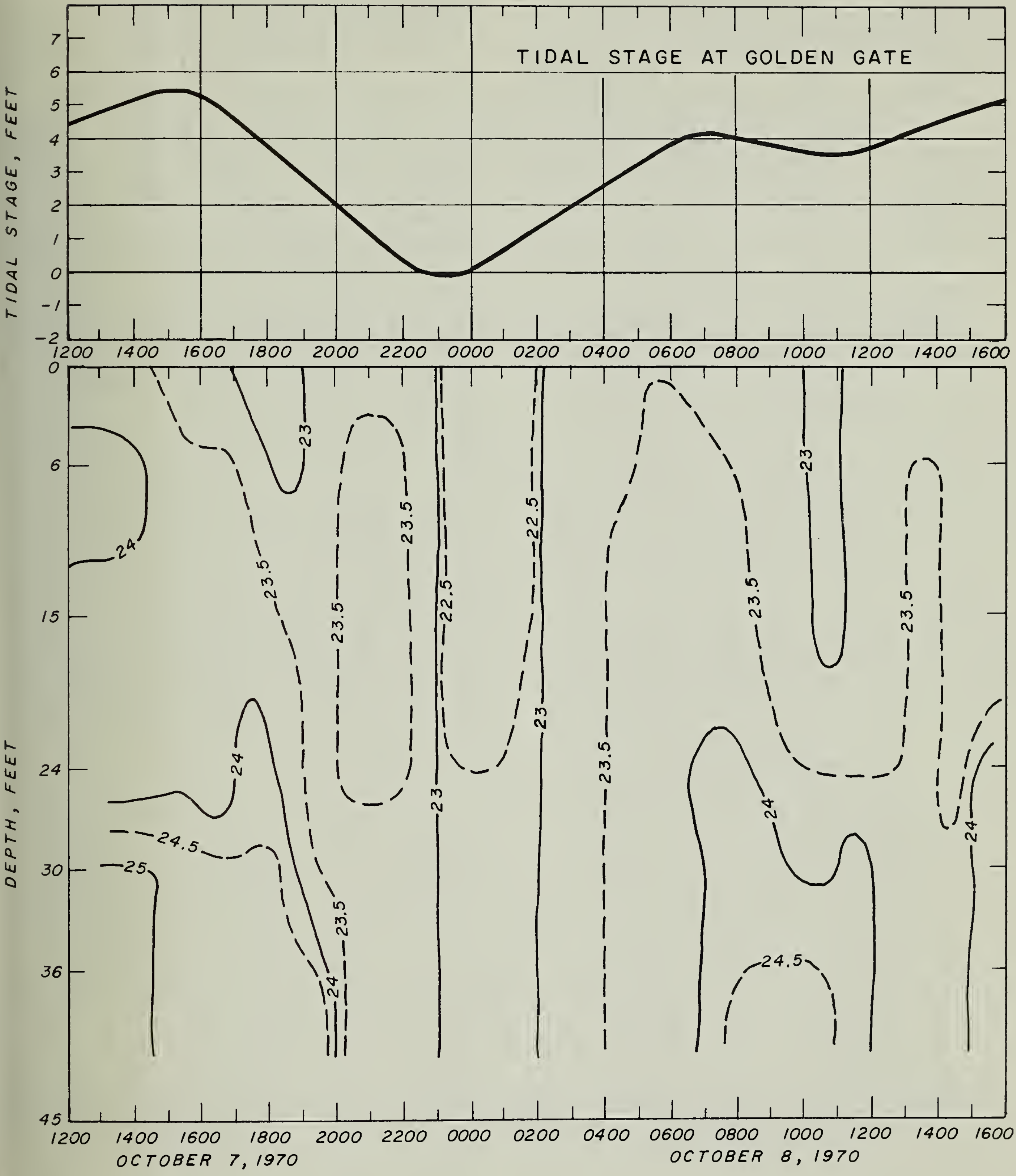


Fig. 4-31 Water Density vs Time & Depth, Station A, Gulf of the Farallones October, 1970

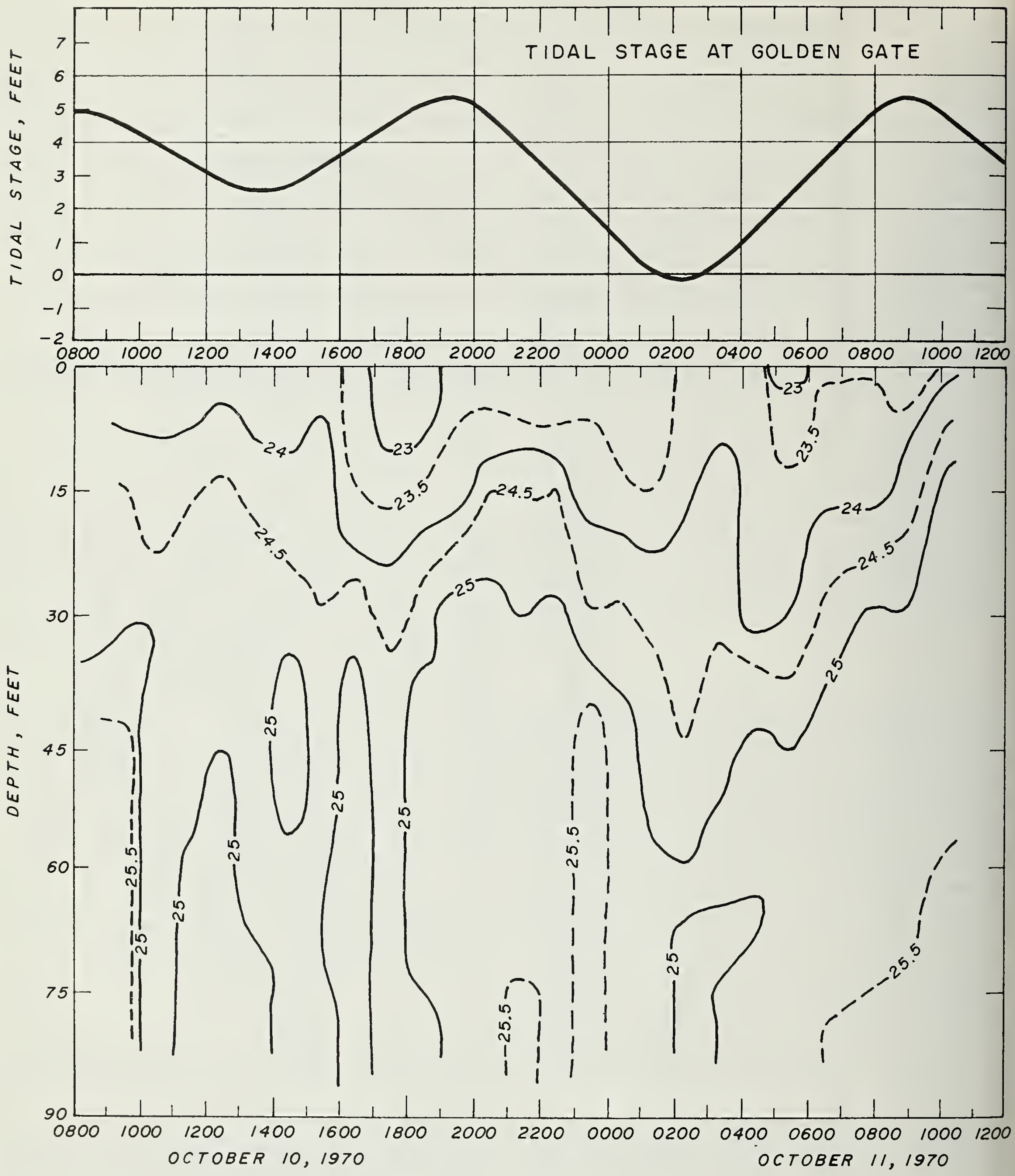


Fig. 4-32 Water Density vs Time & Depth, Station B, Gulf of the Farallones October, 1970

of patch movement does not affect the measurement of dispersion coefficients. Dispersion coefficients determined from the October dye studies are presented in Table 4-5.

Fall Season Surface Drift. Surface drift studies during October were conducted in the same manner as described for June. Procedures were modified slightly based on June experience. Because no bottle caps were found inside the bay during the June studies, five miles of additional bay shoreline was added to the area searched in October. A second change allowed more time for the caps to drift ashore before the search was begun, since June data indicated that several days were required for the bulk of the bottle caps to arrive at the beach. Accordingly, the first sweep of the shoreline was made on October 11, three to five days after the last release. A second sweep was made on October 16 and 17 and produced a significant number of caps, though much smaller than the October 11 sweep.

The field work program called for three cap releases at Station C, near Alcatraz, and four releases at Stations A and B, inside and outside the bar, respectively. The program was carried out as planned, but a field error resulted in two instances of release of the same cap pattern at two different stations. Since there was no way to distinguish the origin of the caps except by pattern, the duplicate releases are identified by both stations on the figures showing results of the study. Thus, Fig. 4-33 shows the results of three releases at Station C and one release at Station A. Fig. 4-34 shows three releases at Station A and one at Station B, and Fig. 4-35 shows the results of three releases at Station B.

The most interesting aspects of the October studies may be summarized as follows:

1. Caps were recovered along the ocean beaches from Point San Pedro to the Bolinas Peninsula, consistent with the June observations.
2. No caps from the ocean releases were recovered inside the bay, also consistent with June observations.
3. Only 16 caps from the Central Bay releases were recovered inside the Golden Gate, and 14 of these were recovered from the Marin Headlands area near Horseshoe Bay. This observation is also in basic conformance with the June data, when no caps were recovered from the bay.
4. Unlike the June results, when no caps were found from any of the bay releases, caps from the October releases inside the bay were found in significant quantities both north and south of the Golden Gate. This may result from the fact that in October the seaward movement of the ebbing water mass was somewhat less than in June.
5. Of the three drops identified exclusively with Station B, caps were recovered from only two. The release from which no caps were recovered was made just before the long ebb swept past the station.

Table 4-5 Dispersion Coefficients in the Gulf of the Farallones, Fall Season

Dye drop time, PDST	Time of measurement, PDST	Axis of measurement[a]	Scale L, feet	Dispersion coefficient K, 10^4 ft^2/hr
October 5, 1970				
1145	1215	X	329.0	8.86
	1228	Y	75.0	0.134
1357	1430	X	367.0	8.73
	1521	X	783.0	6.98
	1417	Y	248.0	5.42
	1447	Z	17.6	0.00256
	1538	Z	18.2	0.0037
1644	1716	X	298.0	5.55
	1708	Y	110.0	13.1
	1729	Z	5.7	0.00107
October 6, 1970				
0954	1028	X	394.0	8.44
	1018	Y	185.0	1.11

[a] X = longitudinal Y = transverse Z = vertical.

Gulf of Farallones, Oceanographic Summary

Oceanographic investigations over a full year produced information describing the characteristics of the study area and the way in which these characteristics are influenced by the seasons. Detailed investigations were conducted on at least two cruises during each of the three basic oceanographic seasons, namely, the winter Davidson Current period, the spring and summer California Current period when upwelling is in progress, and the fall California Current period after upwelling has subsided. All of the information collected ties together to produce a complete description of the oceanographic characteristics of the study area with surprisingly few anomalies. Within the principal area of investigation (Fig. 4-8) the overwhelming influence on oceanographic characteristics is the tidal ebb and flow from San Francisco Bay. The actual area which is strongly influenced by tidal ebb and flow varies with the season of the year, being greatest during the season of high fresh water outflow and smallest during the season of lowest fresh water outflow.

Mass Water Movement. Information obtained through aerial photography, supplemented by surface measurements of the physical-chemical characteristics of the water mass, presents a clear picture of mass water movement. Movement of surface water is shown schematically in Fig. 4-36. As there indicated, the ebbing tide from San Francisco Bay moves strongly westward and southward. During the months of high fresh water outflow the water mass is strongly layered, and the surface ebb lasts longer than the flood. During maximum fresh water outflow the surface flow may ebb continuously.

The distance to which the surface mass moves westward and southward is a function of tidal amplitude and degree of layering. With maximum fresh water outflow and maximum tidal amplitude the bulb of surface outflow may reach westward almost to the Farallon Islands and southward past Point San Pedro.

During the summer and fall months when layering is less pronounced the ebbing tide may move through the area inside the bar in an almost completely mixed condition. However, after crossing the bar the bulb of ebbing water spreads as a surface layer. Even under conditions of minimum tidal amplitude and minimum layering the ebbing tide will reach southward to Lake Merced and westward to the main shipping channel. Rarely does the ebb travel north of the north bar under any conditions.

Once the ebbing surface layer has reached its maximum excursion, it moves comparatively little until moved along by the next ebb. The water which enters the bay on the flood tide comes primarily from the north and south near shore. During the winter this pattern results in the inflow of dense, saline water on the bottom at the same time that less saline water is ebbing on the surface. In the summer and fall months currents are usually in phase on the surface and at depth, but during the flood bottom currents are stronger and during the ebb the surface currents are stronger. These factors combine to produce a high rate of tidal exchange through the Golden Gate, particularly when fresh water outflow is high. The rate of tidal exchange was measured during September, 1970, and is discussed in more detail later in this chapter.

After the surface layer has been displaced westward and southward to the limit of tidal influence, it disperses and diffuses into the oceanic water mass. Within about 24 hours after it leaves the bay, its presence is no longer identifiable as a separate water mass. From that point its movement is presumed to be controlled by the prevailing oceanic currents.

Physical-Chemical Characteristics. The water mass characteristics of particular concern in planning for submarine discharge of sewage effluent are water density, dissolved oxygen content and clarity. The basic patterns of water density were described in the preceding section, but a more specific concern of outfall design is whether stratification will be sufficient to prevent surfacing of an effluent field. In general, the data show that stratification outside the bar to the west is sufficient to maintain a submerged field throughout the year. Inside the bar a submerged field can be maintained during much of the year, but the field will surface occasionally during the summer and fall. Outside the bar to the south a submerged field can be maintained most of the time, but the number of observations in that area is insufficient to guarantee year-round submergence.

Dissolved oxygen content of the ocean surface waters is generally near saturation, and during the summer and fall is higher than in the water ebbing from San Francisco Bay. Dissolved oxygen values inside the bar are generally more representative of Central Bay waters than ocean waters. Outside the bar the bottom layer is typically much lower in dissolved oxygen than is the case in the Central Bay, with values in the range of 4.0 mg/l during the upwelling period.

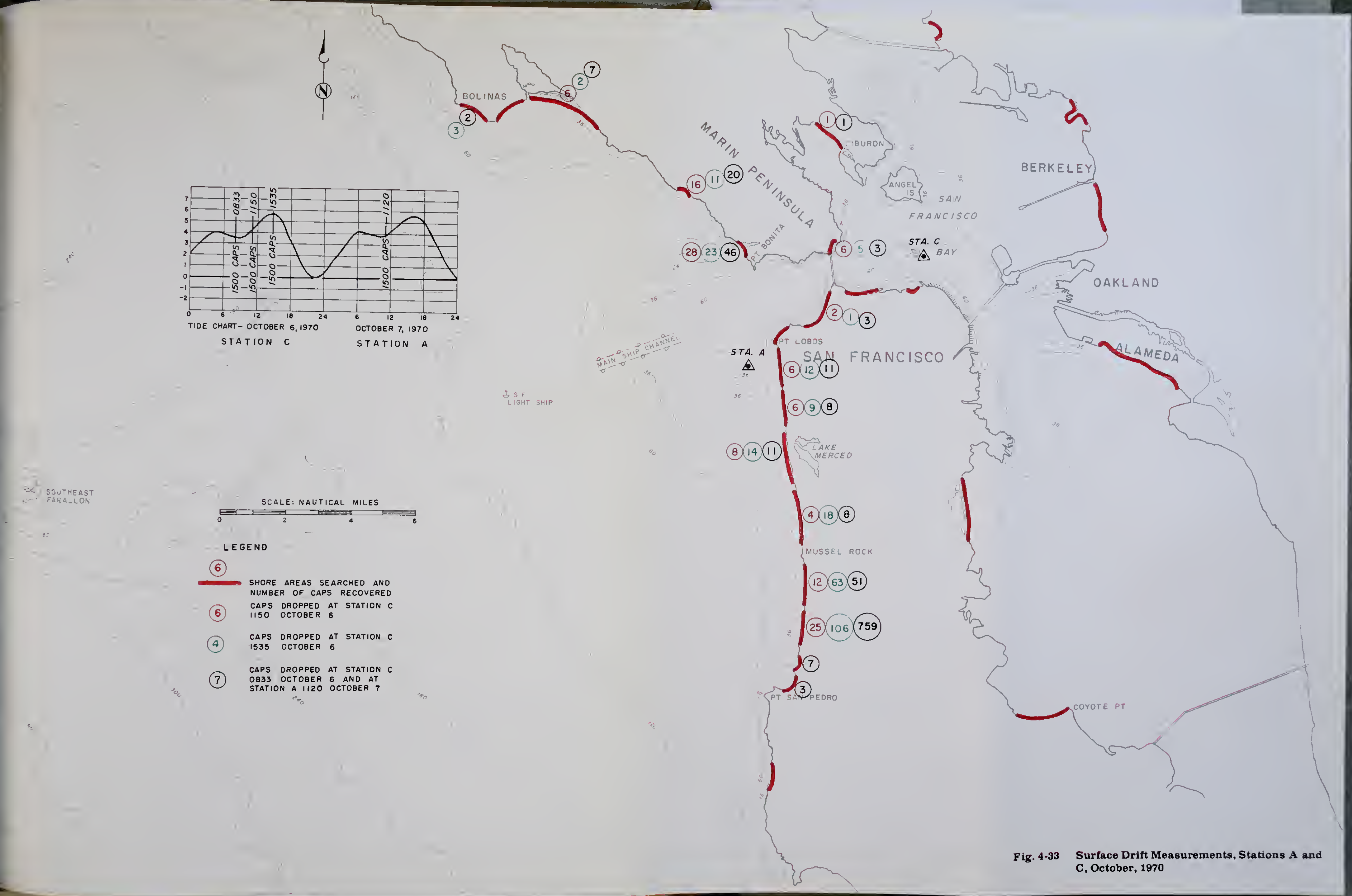


Fig. 4-33 **Surface Drift Measurements, Stations A and C, October, 1970**

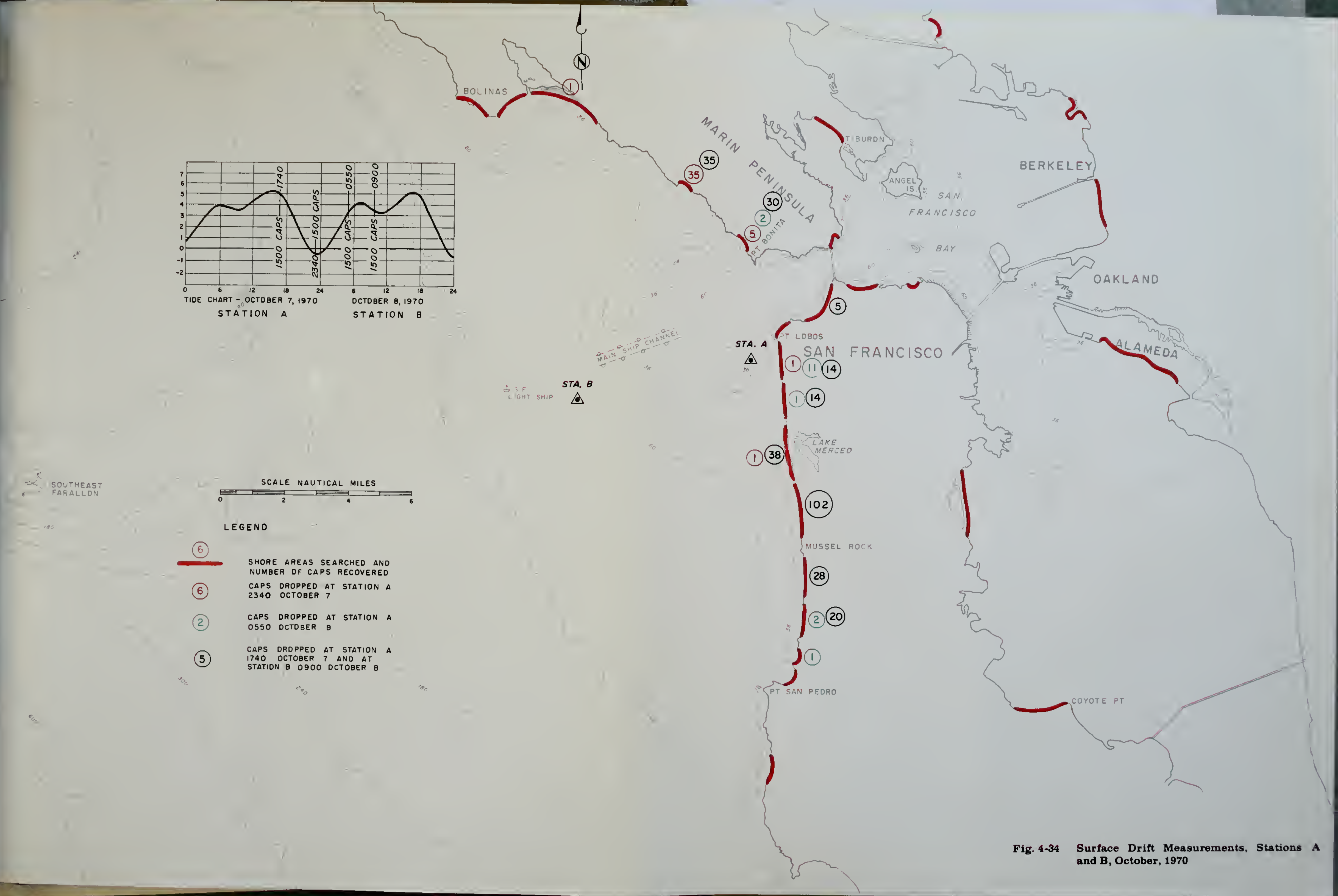


Fig. 4-34 **Surface Drift Measurements, Stations A and B, October, 1970**

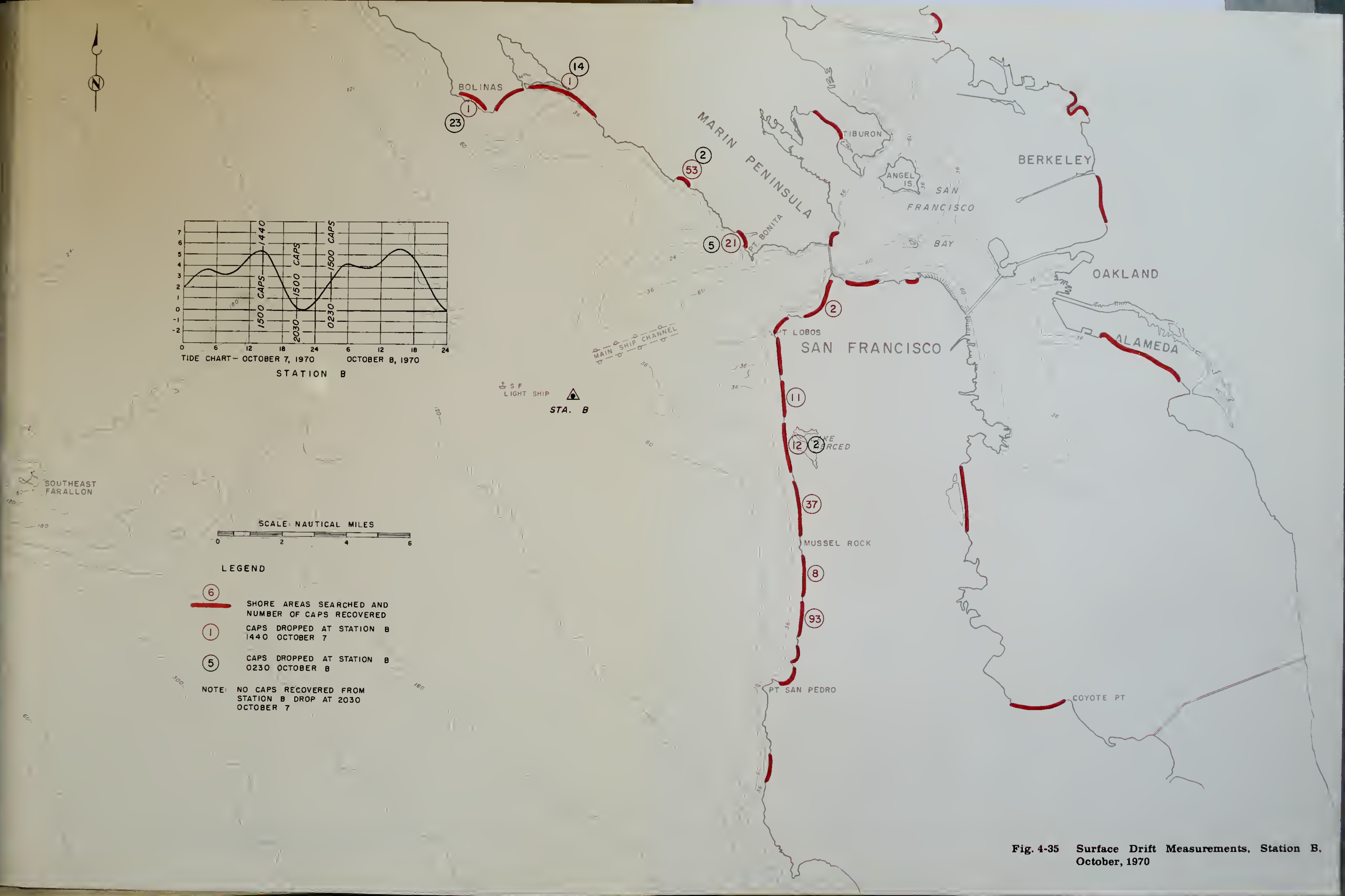


Fig. 4-35 Surface Drift Measurements, Station B, October, 1970

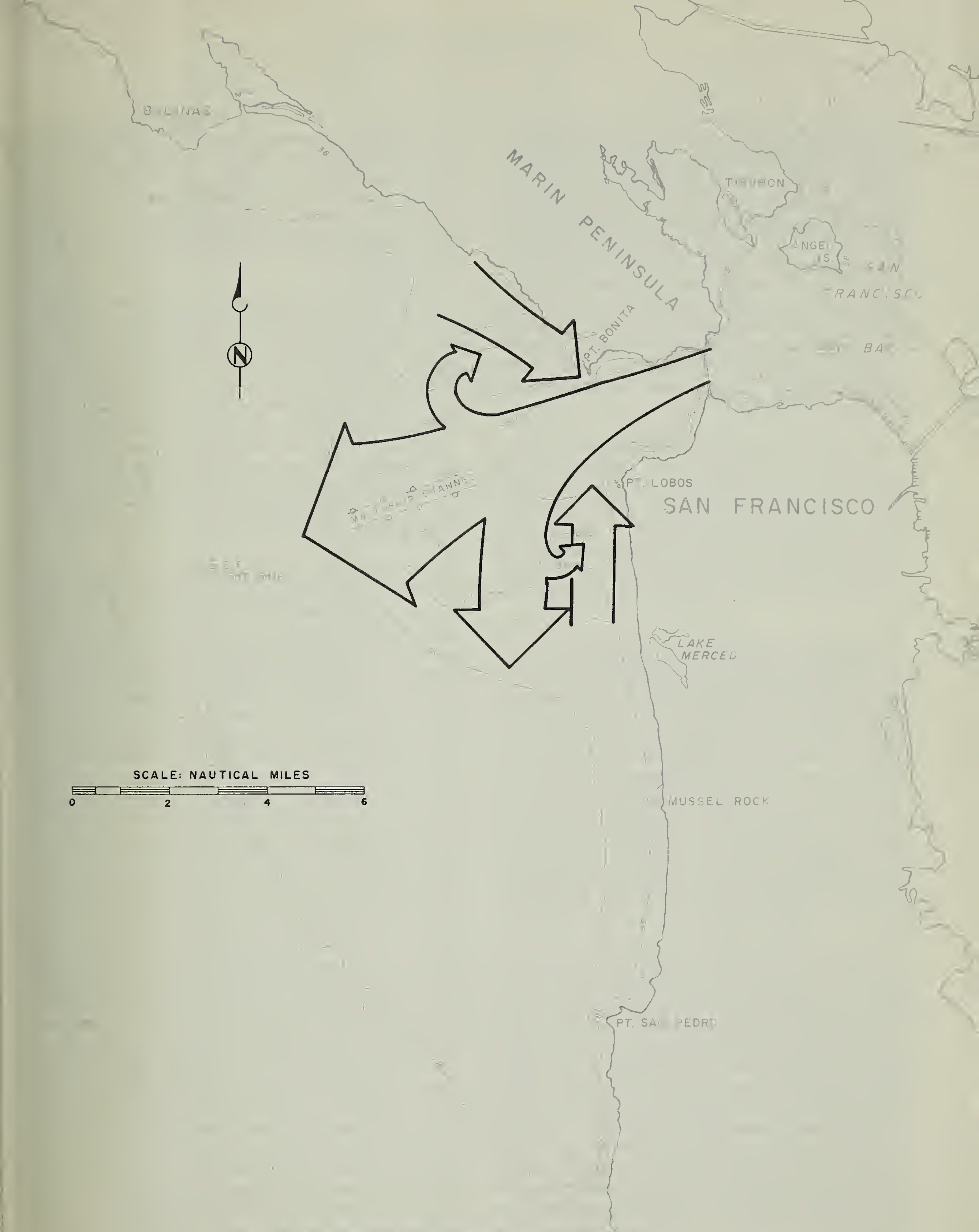


Fig. 4-36 Schematic Diagram of Surface Advection Gulf of the Farallones

Water clarity in the study area varies both diurnally and seasonally because of the influence of the ebb from San Francisco Bay. As measured by Secchi disc, water clarity varied from a low of 1.5 ft inside the bar in February to a high of 26 ft outside the bar in October. As a general rule, the water flowing out of San Francisco Bay reduces water clarity in the Gulf of the Farallones. This is the phenomenon which made it possible to track mass water movement by aerial photography. Since the water flowing out of the bay is most turbid in the winter and least turbid in the late summer and fall, the water in the Gulf of the Farallones which is influenced by bay outflow responds accordingly.

Currents. Current data are presented in detail in Volume 2, Data Supplement, in graphic and tabular form. As a capsule summary it can be stated that maximum currents occur during the season of high fresh water outflow, and that the strongest currents occur closest to the mouth of the Golden Gate. Outside the bar bottom currents are small and surface currents seldom exceed one knot.

Dispersion Coefficients. Dispersion coefficients experimentally determined in the Gulf of the Farallones for each of the seasons investigated are presented in Tables 4-2, 4-3 and 4-5. After the field work was completed, all coefficients were analyzed to establish a mathematical basis for prediction of the turbulent diffusion of an effluent field. Several environmental factors were postulated to be important in establishing the rate of of diffusion as measured by the dispersion coefficients. Among these were current, wind condition, wave height, degree of stratification and scale of the diffusion phenomenon. However, attempts at correlation were negative for all factors except scale.

Horizontal diffusion along the major and minor axes in the Gulf of the Farallones was found to be strongly a function of scale, in this case defined as the average scale over the period of measurement. Fig. 4-37 presents the measured dispersion coefficients for the Gulf of the Farallones plotted against an index of the average scale. The plot presents the best-fit curves as computed by least squares and as plotted in accordance with the so-called "four-thirds law". For comparison, Pearson's four-thirds law correlation of dispersion coefficients for other ocean measurements is also shown. The Gulf of the Farallones data points are mostly well above Pearson's line, indicating that dispersion takes place at a faster rate than in most coastal areas. This may be postulated to result from a higher level of turbulence created by the massive tidal flows through the Golden Gate. The four-thirds law relationship shown in Fig. 4-37 ($k=20\ L^{4/3}$) was used for all applications to waste field dispersion, since it has a theoretical basis founded in fundamental turbulence theory.[17]

The lack of correlation of horizontal dispersion with current and wind measurements is similar to the findings of Foxworthy,[31] who investigated dispersion in the coastal waters of Southern California. The apparent lack of correlation does not imply that current, wind and possibly other factors do not affect dispersion; it simply means that these factors are overshadowed by the influence of scale. Of considerable interest is the fact that neither the season of the year nor the location within the study area exert any discernible influence on dispersion coefficients.

Surface Drift. Two quantitative studies of surface drift were conducted, one during June and one during October. In all, 30,000 cardboard milk bottle caps were released at five different stations in the Central Bay and Gulf of the Farallones. A summary of the information on release and recovery for all stations is presented in Table 4-6. The information indicates that the location where floatable material comes ashore is a function of the tidal condition at the time of release, but the relationshop is too complex to be clearly defined by the work done in connection with this study. One factor involved is the tendency of floatable material to accumulate in a line along the leading edge of an ebbing tide. This is caused by the fact that surface velocity at the forward edge of the ebbing water mass is more rapid than subsurface velocity, with the result that the surface layer flows forward to the color line at the edge of the ebb and is pulled below the surface by shear with the underlying water mass which is being overridden. Floatable material is not pulled below the surface, but accumulates in a debris line along the forward edge of the ebb. By the end of the ebb, a considerable quantity of floatable material has accumulated in the debris line. This material then drifts ashore due to wind action, sometimes arriving at the beach in fairly concentrated amounts.

The data reported in Table 4-6 represent a total of 20 releases at different locations and tidal conditions, and the composite analysis of these results may be considered to represent something approaching a steady state condition. Several

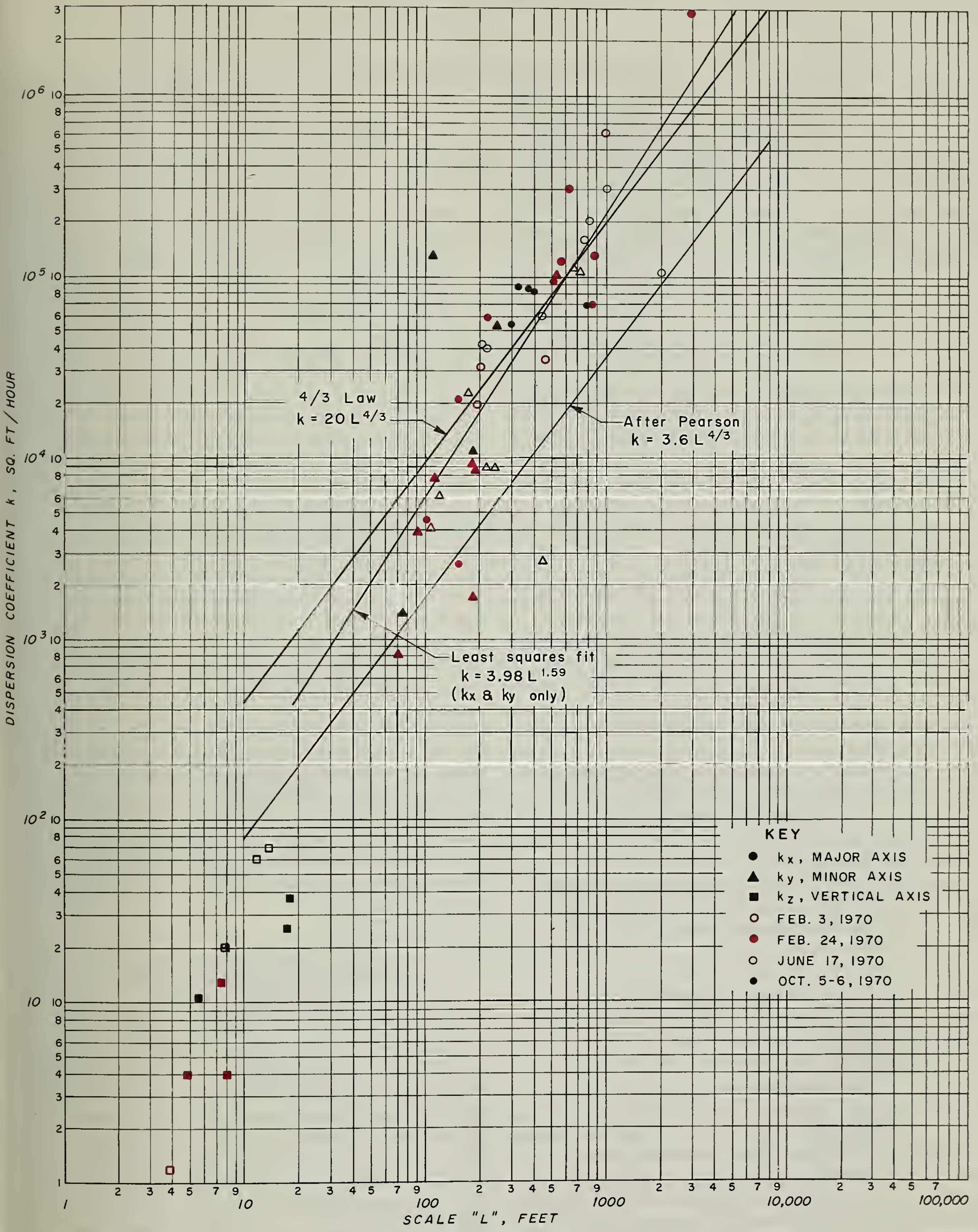


Fig. 4-37 Dispersion Coefficients in the Gulf of the Farallones

Table 4-6 Surface Drift Summary

Item	June, 1970 stations[a]			October, 1970 stations[b]					Totals
	X	Y	Z	A	B	C	A&C	A&B	
Caps dropped	4500	4500	4500	3000	4500	3000	3000	3000	30,000
Caps recovered									
Inside Golden Gate	0	0	0	0	0	12[c]	4[c]	0	16
North of Golden Gate	8	0	0	43	120	89	75	65	400
South of Golden Gate	707	1140	0	17	165	286	861	221	3397
Miles of shoreline searched									
Inside Golden Gate	11.7	11.7	11.7	16.6	16.6	16.6	16.6	16.6	
North of Golden Gate	5.5	5.5	5.5	6.9	6.9	6.9	6.9	6.9	
South of Golden Gate	14.2	14.2	14.2	16.0	16.0	16.0	16.0	16.0	
Caps per mile of shoreline									
Inside Golden Gate	0	0	0	0	0	0.7	0.3	0	1.0
North of Golden Gate	1.5	0	0	6.3	17.4	12.7	10.9	9.6	58.4
South of Golden Gate	49.2	80.3	0	1.0	10.4	17.8	53.9	13.8	226.4
Caps per mile of shoreline as a percentage of all caps released									
All ocean shoreline	0.8	1.3	0	0.09	0.3	0.5	1.4	0.4	
North of Golden Gate	0.03	0	0	0.2	0.4	0.4	0.4	0.3	0.2
South of Golden Gate	1.1	1.8	0	0.03	0.2	0.6	1.8	0.5	0.8

[a] See Figs. 4-24 and 4-25.

[b] See Figs. 4-33, 4-34, and 4-35.

[c] Of the 16 caps recovered inside the bay, 14 were recovered near Ft. Baker.

important conclusions can be derived from the data summary:

1. Floatables discharged in the Central Bay in the vicinity of Alcaltraz will not accumulate on the bay shoreline in significant quantities.
2. Floatables released outside the Golden Gate will not enter the bay.
3. The heaviest accumulation of floatable material from outfall sites reasonably available to the City of San Francisco will occur on beaches to the south of the Golden Gate.
4. The number of caps recovered per mile of ocean shoreline where caps were found varied from 0 to 1.8 percent of the total released, with average values of 0.2 percent north of the Golden Gate and 0.8 percent south of the Golden Gate.

From observations during the cap recovery operation it was concluded that at least half of the number of caps that reach the shoreline were recovered and counted. The remainder may have been buried by wave action, blown away by the wind or trampled into the sand by people on the beaches. If a conservative 50 percent recovery is assumed, and if the action of the bottle caps is assumed to represent accurately the behaviour of floatables of sewage origin, then the percent recovery per mile of shoreline may by applied to the mass emission of floatables as a design parameter. On that basis, floatables released at or near any of the sites investigated could be expected to accumulate on the shoreline at a rate of 1.6 percent per mile south of the Golden Gate from Point Lobos to Point San Pedro and 0.4 percent per mile north of the Golden Gate from Point Bonita to Bolinas Peninsula.

PHYSICAL OCEANOGRAPHY OF SAN FRANCISCO BAY

Unlike the Gulf of the Farallones, where past oceanographic work has been quite limited, San Francisco Bay has been the subject of intensive investigation in recent years. Of major importance is the study by Pearson, et al entitled "A Comprehensive Study of San Francisco Bay".[1] That study presents an impressive catalogue of physical, chemical and biological information on Central San Francisco Bay. By using the data from the above-referenced work as the primary reference source on water quality, it was possible to focus the efforts of the present study on the dynamics of the water mass in those areas of particular concern to the City of San Francisco.

Because of its hundred-year history as a major port, San Francisco Bay has received vastly more attention from oceanographers and hydrographers than the Gulf of the Farallones and the open ocean. Since they are of special importance to navigation, currents in particular have been studied in detail on a number of occasions. These studies have shown, as might be expected, that tidal ebb and flow is the single factor of overriding importance in the movement of water through the Central Bay. Compared to the volume of the tidal prism, even the historic maximum outflow of fresh water through the bay and delta system is small. The changing seasons therefore cause some definite changes in water quality and modify the pattern of mass water movement, but the basic flow patterns remain unchanged throughout the year. For this reason there is no particular value in considering the separate seasons independently as was done for the Gulf of the Farallones. Instead, each parameter of interest is discussed separately in the following pages, and the effect of seasonal changes is included in that discussion. Those parameters of particular interest in defining the dynamics of waste dispersal are currents, mass water movement, horizontal dispersion and surface drift. The limited physical-chemical measurements conducted in connection with this study are presented and discussed in relation to the larger mass of previously published data. Measurements of surface drift in the Central Bay were described earlier along with surface drift studies in the Gulf of the Farallones.

Currents

The mass of recent current data available from the U. S. Coast and Geodetic Survey[23] made it unnecessary to conduct further current measurements in connection with this study. Current direction and average and maximum velocity during both flood and ebb at each of the 36 bay stations shown on Fig. 4-4 are tabulated in Volume 2, Data Supplement. The data from these measurements were used by the U. S. Coast and Geodetic Survey in the preparation of tidal current charts for San Francisco Bay.

The portion of the Central Bay which is of the most interest to the City of San Francisco for waste disposal planning lies within about 8,000 ft of the city shoreline, roughly the distance to Alcatraz Island and Yerba Buena Island. In this zone currents run approximately parallel to the shoreline on both ebb and flood. Current velocities vary from ebb to flood, surface to bottom and of course from station to station. In general, the ebb cycle has higher current velocities but a shorter duration than the flood cycle. Surface currents typically have a higher velocity than bottom currents, and this difference is greatest on the ebb cycle. Maximum surface velocities commonly run in excess of 3 K, and occasionally exceed 4 K. Along the bottom maximum velocities are generally less than 2 K.

Mass Water Movement

The pattern of mass water movement in the Central Bay adjacent to the City of San Francisco is well defined and changes very little with the seasons. On the flood tide water flows through the Golden Gate, parallels the San Francisco shoreline through the channel between North Point and Alcatraz, passes under the Bay Bridge west of Yerba Buena Island, and flows southward into the South Bay. On the ebb tide the water reverses direction and retraces its course.

Advective flow diagrams of currents at the stations of principal interest to the City of San Francisco are presented in Volume 2, Data Supplement. The data supplement also contains a table of mass displacement vectors for each station at various depths. Each mass displacement vector represents the summation of hourly vectors at the designated station over a complete tidal cycle. Currents at most of the stations were measured during February and March, and therefore represent the wet weather flow condition. However, a few stations, including Stations 35 and 36 (Fig. 4-4) in Alcatraz Channel, were measured in August and September. These measurements give an indication of conditions which obtain during dry weather.

Wet Weather Conditions. Advective flow diagrams for the bay south of the Bay Bridge show mass water movement as indicated by current measurements in February, 1952 at Stations 9, 10, 13 and 14 (Fig. 4-4). The diagrams clearly show a net northerly (seaward) flow on the surface and a net southerly flow on the bottom, indicating that the salt water wedge which was measured at the Golden Gate flows southward at least as far as Hunters Point. This layered flow pattern, which is typical for the entire Central Bay during the wet weather period, assures the seaward movement of the surface layer. South of the Bay Bridge the net seaward displacement is small compared to the

During the winter season on an ebb tide highly tirbid water from the Sacramento-San Joaquin River system flows through the Central Bay in a surface layer. The less turbid water flowing out of the South Bay is in the foreground.

Central Bay, but still amounts, typically, to several miles per tidal cycle.

Immediately west of the Bay Bridge the seaward displacement of the surface layer increases tremendously. Seaward displacement vectors of 10 to 25 nautical miles per tidal cycle were measured for the surface layer in February and March of 1952. The advective flow diagrams for the area from the Bay Bridge through Alcatraz Channel all show massive seaward displacement of the surface layer and only minor bayward movement of the bottom layer. Since the amount of water flowing out of the South Bay must be equal to the water flowing into it, and since fresh water inflow to the South Bay is insignificant in comparison with the volume of the tidal prism, it must be concluded that the surface layer of high seaward advection is shallow compared to the bottom layer of lower bayward advection.

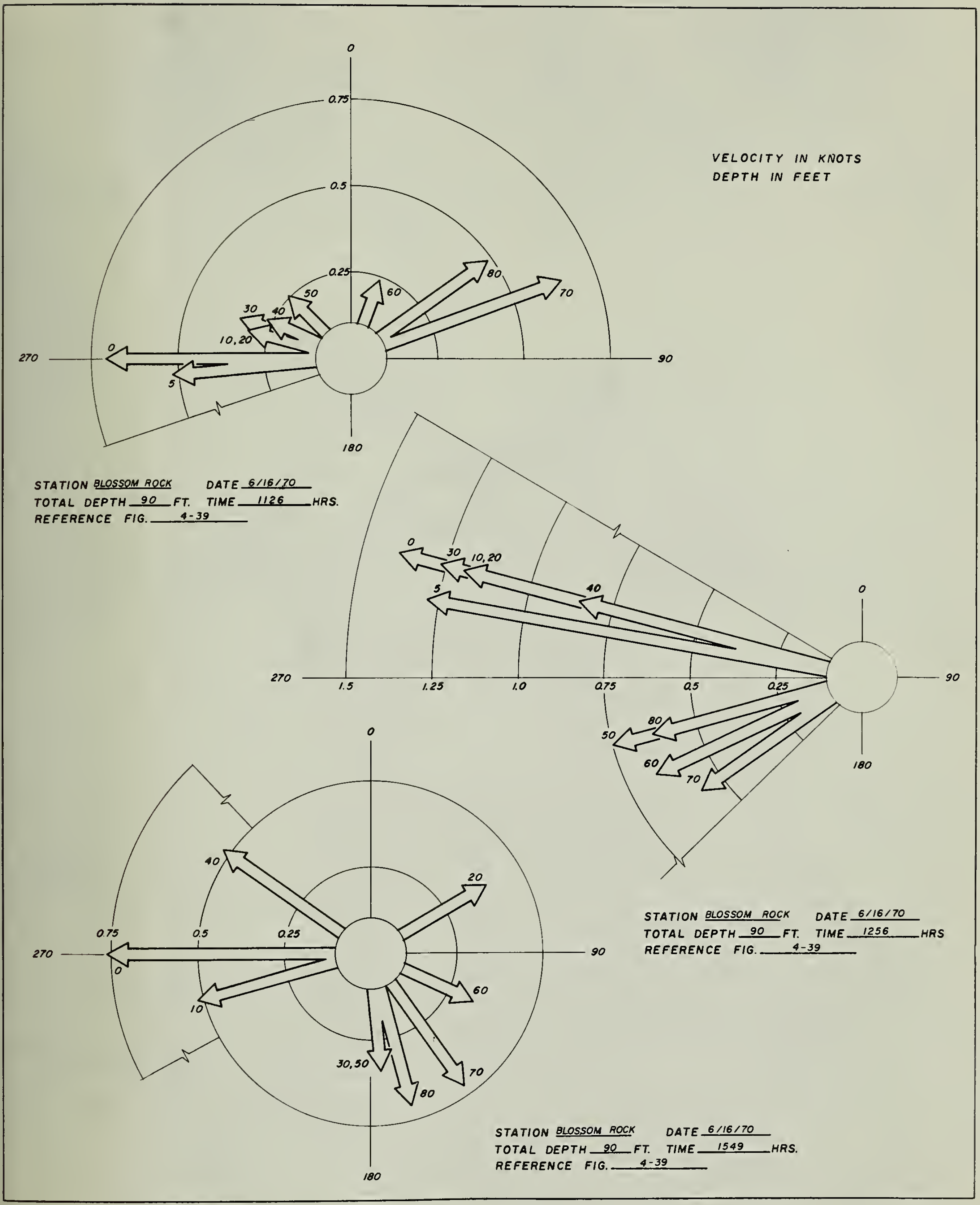
The phenomenon of strong seaward displacement of the surface layer through Alcatraz Channel is of major importance to the disposal of wastes in wet weather. A waste field discharged to the surface layer at any point west of the Bay Bridge during wet weather will be removed from the bay by a seaward displacement of six miles or less. Since the seaward displacement vectors computed for this area have values of 10 to 25 miles per 25-hr tidal cycle, the mean residence time of a surface waste field in the bay would be less than one tidal cycle and probably less than 12 hours.

Dry Weather Conditions. Current information for San Francisco Bay during the dry weather condition is more limited than that for wet weather, but two of the USC&GS stations in Alcatraz Channel were measured during August and September 1953. In addition, current profiles were measured in the vicinity of Blossom Rock on June 16, 1970 in connection with this study.

The advective flow diagrams presented in the data supplement show that by the end of the summer season the massive seaward displacement of the surface layer has subsided. There remains a small but distinct seaward component in the surface layer, and an approximately balancing bayward component in the bottom layer. The nature of the layered flows is illustrated by the current profiles taken at Blossom Rock on June 16, 1970 (Fig. 4-38). The station depth is 90 ft, and the profiles show that the separation between layers is about at mid-depth. The first profile, taken at 1126 hrs, shows currents at the time of reversal from flood to ebb. On the surface the reversal had already occurred, and the current was ebbing about 0.7 K. Near the bottom, however, the flood current was still running at more than 0.5 K. By 1256 hrs the ebb current was well developed, but currents below mid-depth were in a slightly different direction at about half the velocity of the surface currents. Reversal from ebb to flood occurred at about 1549 hrs, and the current vectors show that the flood current was developing below mid-depth while the surface was still ebbing.

Further confirmation of surface layer mass movement during dry weather was provided by the movement of dye patches dropped in connection with the measurement of dispersion coefficients. Cruises in the Central Bay were conducted during June, August and October, 1970. Location and scope of the oceanographic measurements for each cruise are shown on Figs. 4-39, 4-40 and 4-41. Oceanographic efforts were centered in Alcatraz Channel, because one of the principal objectives of the study involved recommendations for the disposal of effluent from the North Point water pollution control plant.

The movement of dye patches throughout the three cruises confirmed tha information obtained from analysis of USC&GS current data. Dye drops on August 20-21 (Fig. 4-40) were made on a maximum flood tide, and consecutive drops were made to track the movement of the water mass into the South Bay. Altogether, the dye patch observations covered about two-thirds of the flood cycle, and the dye patches moved southward as far as

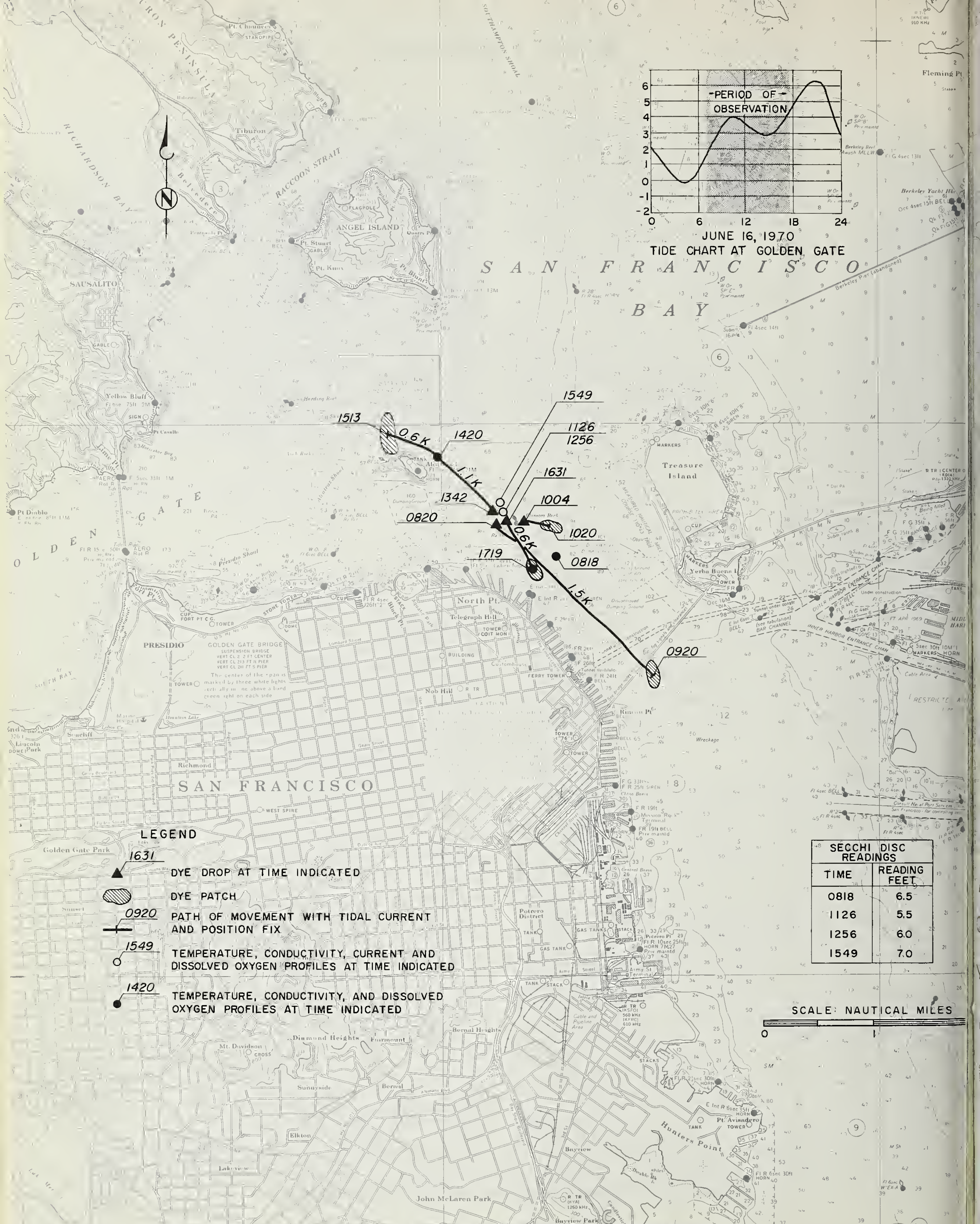


STATION BLOSSOM ROCK DATE 6/16/70
TOTAL DEPTH 90 FT. TIME 1126 HRS.
REFERENCE FIG. 4-39

STATION BLOSSOM ROCK DATE 6/16/70
TOTAL DEPTH 90 FT. TIME 1256 HRS
REFERENCE FIG. 4-39

STATION BLOSSOM ROCK DATE 6/16/70
TOTAL DEPTH 90 FT. TIME 1549 HRS.
REFERENCE FIG. 4-39

Fig. 4-38 **San Francisco Bay Current Profiles with Depth**



SECCHI DISC READINGS

TIME	READING FEET
0818	6.5
1126	5.5
1256	6.0
1549	7.0

Fig. 4-39 Physical Oceanography in San Francisco Bay, June 16, 1970

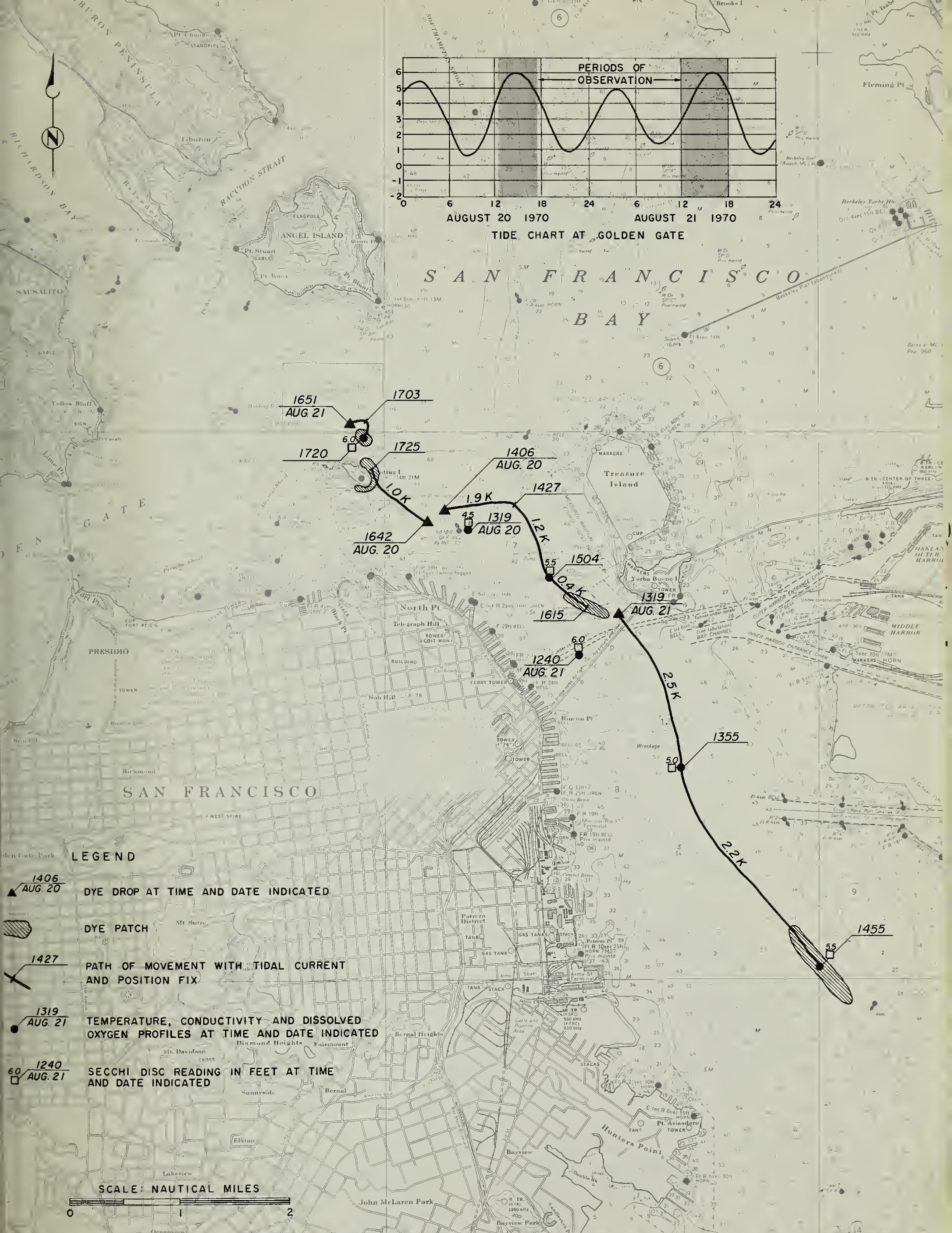


Fig. 4-40 Physical Oceanography in San Francisco Bay, August 20-21, 1970

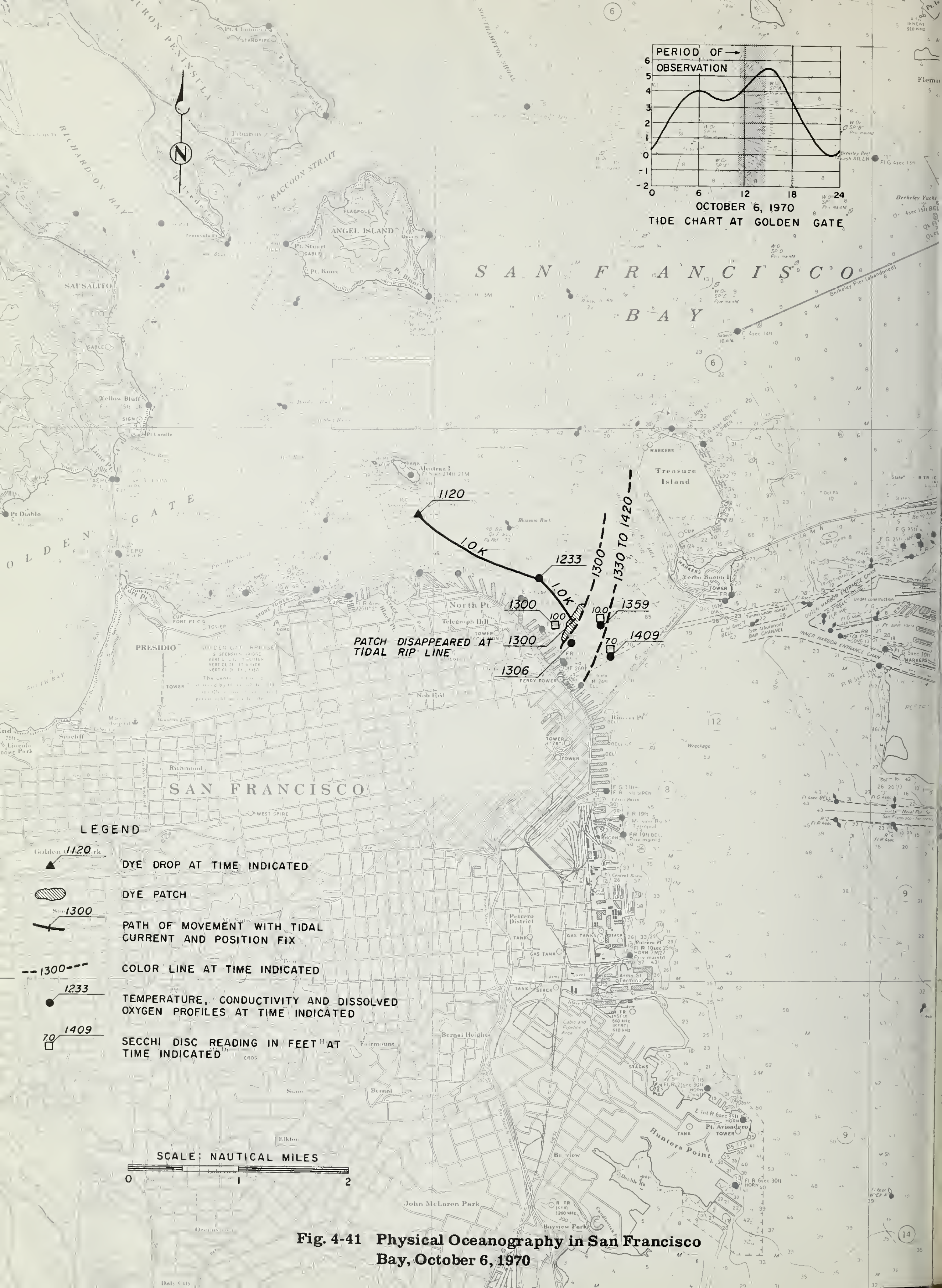

PERIOD OF OBSERVATION
6
5
4
3
2
1
0
-1
-2
0
6
12
18
24
OCTOBER 6, 1970
TIDE CHART AT GOLDEN GATE
SAN FRANCISCO BAY
1120
1.0 K
1233
1.0 K
1300
1330 TO 1420
1300
100
1359
70
1409
PATCH DISAPPEARED AT TIDAL RIP LINE
1300
1306
SAN FRANCISCO
GOLDEN GATE
ANGEL ISLAND
Treasure Island
Alcatraz I
PRESIDIO
Hunters Point
LEGEND
1120
DYE DROP AT TIME INDICATED
DYE PATCH
1300
PATH OF MOVEMENT WITH TIDAL CURRENT AND POSITION FIX
1300
COLOR LINE AT TIME INDICATED
1233
TEMPERATURE, CONDUCTIVITY AND DISSOLVED OXYGEN PROFILES AT TIME INDICATED
70
1409
SECCHI DISC READING IN FEET AT TIME INDICATED
SCALE: NAUTICAL MILES
0
1
2
N

Fig. 4-41 Physical Oceanography in San Francisco Bay, October 6, 1970

Islais Creek. Over a maximum flood cycle an effluent field released near North Point would move southward to a point about two miles south of Hunters Point. However, on the following ebb the field would move back into the Central Bay to a point seaward of its starting point.

On October 6 a dye patch dropped in Alcatraz Channel on a flood tide moved southeast until it reached a color line stretching from about the Ferry Building to Treasure Island (Fig. 4-41). The dye patch ducked under the color line and disappeared. Previous work in the Gulf of the Farallones had shown that the presence of a color line is an indication that one water mass is overriding another of greater density. About 30 minutes later a portion of the dye patch resurfaced near the Bay Bridge, aparently as a result of vertical turbulence around the center pier of the bridge. At this point the dye patch was over half a mile behind the color line, providing further evidence of the fact that even in the period of minimum fresh water outflow there is a net seaward displacement of the surface layer in the bay.

Dispersion Coefficients.

Dispersion coefficients for the cruises in June, August and October were determined using the same techniques described previously for the work in the Gulf of the Farallones. The physical location of the dye patches used in determining dispersion coefficients is shown in Figs. 4-39, 4-40 and 4-41.

Dispersion coefficients were also obtained from analysis of data from a steady state dye study of the North Point outfall conducted on April 22, 1970 and described in detail later in this chapter. The horizontal spread of a sewage field from a point source can be described by the following equation:

$$\sigma = \sqrt{2kt} \qquad \textbf{(10)}$$

where t is the time of travel from a point source. Rearranging Equation 10 yields the dispersion coefficients:

$$ky = \frac{\sigma^2 y}{2t} \qquad \textbf{(11a)}$$

$$kz = \frac{\sigma^2 z}{2t} \qquad \textbf{(11b)}$$

Equation 11 is valid for steady-state releases, a condition not exactly obtained under release into a water mass with strong tidal fluctuations. However, if the measurements are taken for the condition where the time since tidal reversal is significantly longer than time t, Equations 11a and 11b can be reasonably applied. Three transects from the steady-state study at the North Point outfall satisfied this criterion, and two horizontal and one vertical dispersion coefficients were derived from them. Dispersion coefficients for San Francisco Bay from all cruises are listed in Table 4-7.

As was the case for dispersion in the Gulf of the Farallones, no correlation was found between horizontal dispersion in San Francisco Bay and current, wind, season or degree of stratification, but a definite correlation with scale was found to exist. In Fig. 4-42 all dispersion coefficients for San Francisco Bay are plotted against scale. As the figure shows, the least squares fit of the data corresponds quite closely to the line representing the so-called four-thirds law curve, which was adopted for the definition of horizontal dispersion in San Francisco Bay. The formula for that curve is $k = 33 L^{4/3}$. For comparison, Fig. 4-42 also shows the relationship developed by Pearson[32] for coastal waters, $k = 3.6 L^{4/3}$. Dispersion coefficients for San Francisco Bay as developed for this study are thus approximately one order of magnitude higher than the values measured by other observers under open ocean conditions. The higher rate of dispersion within the bay may be the result of currents which are considerably higher than those found in most coastal areas.

In applying dispersion equations to an effluent field in San Francisco Bay it must be remembered that the bay is an enclosed body of water, and the shoreline represents a natural limit to horizontal dispersion. Horizontal dispersion will therefore increase with time and scale in accordance with the relationship shown in Fig. 4-42 only until the edge of the effluent field reaches the shoreline.

Physical-Chemical Characteristics.

The physical and chemical characteristics of Central San Francisco Bay were carefully defined by Pearson, et al, in “A Comprehensive Study of San Francisco Bay”.[1] The fourth annual report in that study covers a full year of sampling in Central San Francisco Bay. The data collection in connection with this study generally support and confirm the information presented by Pearson. The particular concern of this study was to develop additional information on the variation of water density with depth, since this factor is of major importance in predicting the performance of a submerged effluent diffuser.

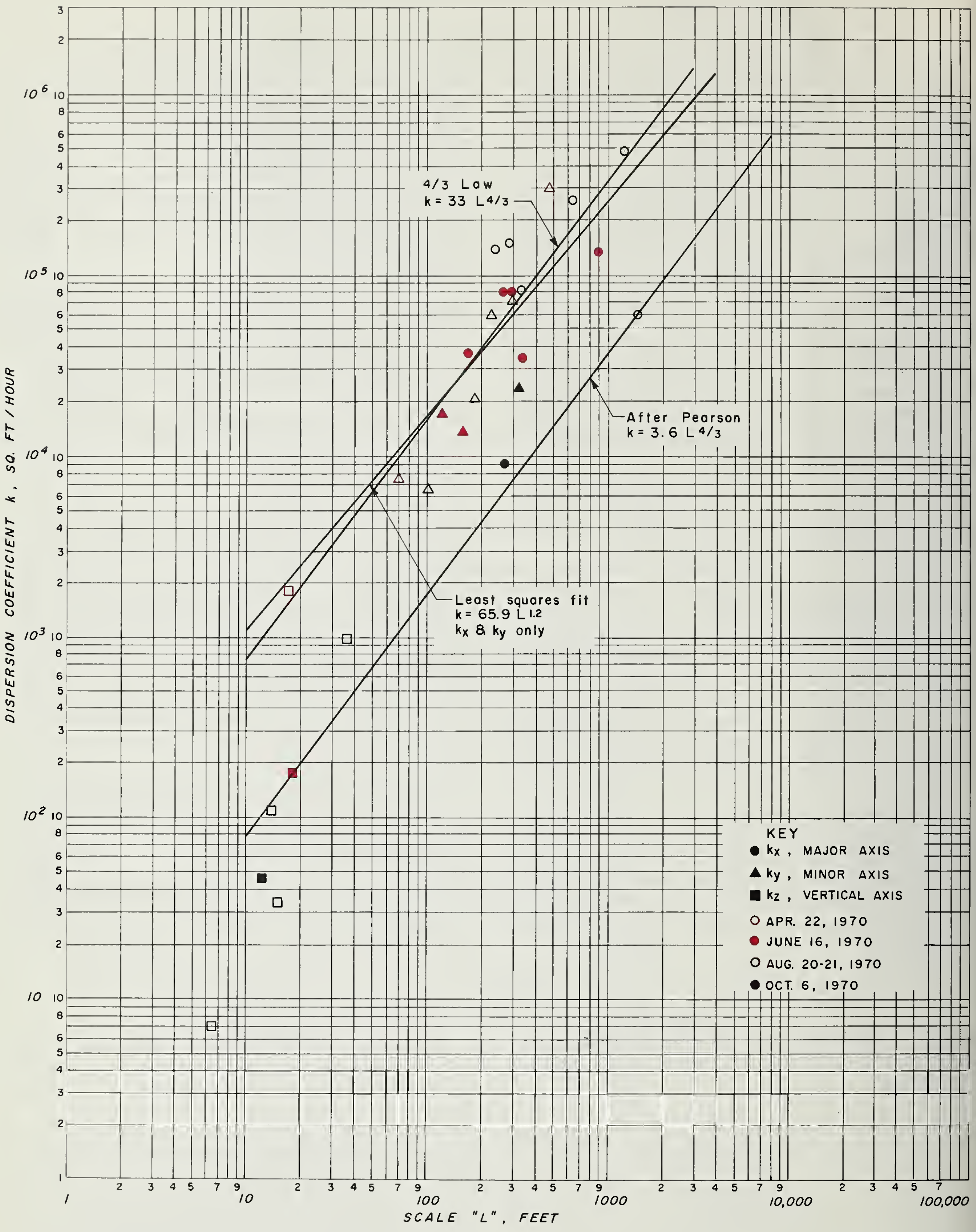


Fig. 4-42 Dispersion Coefficients in San Francisco Bay

Table 4-7 Dispersion Coefficients in San Francisco Bay

Date	Dye drop time PDST	Time of measurement	Axis of measurement[a]	Scale L feet	Dispersion coefficient K, 10^4 ft^2/hr
June 16, 1970	0802	0920	X	332.0	3.59
	1004	1019	X	165.0	3.80
	1342	1407	X	284.0	7.95
		1509	X	877.5	14.20
		1356	Y	120.0	1.75
		1427	Z	17.7	0.0175
	1631	1652	X	258.5	7.95
		1707	Y	156.7	1.37
August 20, 1970	1402	1449	X	630.0	27.1
		1616	X	1428.5	6.0
		1428	Y	283.0	7.65
		1512	Z	10.5	0.0034
	1651	1724	X	331.0	8.45
August 21, 1970	1324	1333	X	232.7	14.2
		1438	X	1221.0	47.8
		1344	Y	224.1	6.0
		1420	Y	185.0	2.05
		1406	Z	13.8	0.011
		1504	Z	6.5	0.0007
	1651	1704	X	282.8	15.3
		1714	Y	100.9	0.65
		1728	Z	36.5	0.099
October 6, 1970	1120	1221	X	268.2	0.899
		1209	Y	322.5	2.38
		1237	Z	12.6	0.0047
April 22, 1970[b]		Flood tide	Y	70	0.769
		Ebb tide	Y	460	30.5
		Ebb tide	Z	16.5	0.191

[a] X = longitudinal Y = transverse Z = vertical

[b] Dispersion coefficients derived from steady-state dye release study of existing North Point outfall.

Temperature-Salinity-Density Profiles. Temperature and salinity profiles were collected during February, April, June, August and October of 1970 for an area of the bay from the Golden Gate Bridge to Islais Creek and extending about two miles offshore from the City of San Francisco. Plotted profiles of temperature, salinity and density for each observation are included in Volume 2, Data Supplement. Plots for June, August and October also include profiles of dissolved oxygen.

As would be expected from the analysis of mass water movement, the density profiles indicate that some degree of density stratification is present in the bay all year long. The February profiles clearly show the effect of high fresh water outflow from the Delta, which produced massive stratification and median salinity values in the Central Bay of about 22 ppt. This corresponds to a median chlorosity value of about 12 to 13 ppt, which is substantially lower than the minimum values reported by Pearson.[1] The lowest measured value for salinity was 7.4 ppt in a surface reading on February 3, 1970.

By April the massive stratification had disappeared. Differences between surface and bottom salinity of 1 to 2 ppt were common, but occasional profiles showed complete vertical mixing with little or no stratification. This pattern continued throughout the remainder of the year. Median salinity varied through the spring and summer approximately as documented by Pearson, but there was little change in the degree of stratification.

Dissolved oxygen values in the Central Bay were consistently about 7.0 mg/l at the surface, though values at depth occasionally dropped below that value. The minimum value measured for dissolved oxygen was 6.0 mg/l.

Water Clarity. As in the Gulf of the Farallones, a Secchi disc was used to measure water clarity. Pearson, et al,[1] reported Secchi disc readings and suspended solids measurements for the Central Bay. Except for the high values of suspended solids there is no correlation between the two.

The Water Quality Control Board normally couches its water clarity requirements in terms of turbidity and "apparent color". If apparent color is defined as an observable phenomenon, then the Secchi disc is a reasonable instrument for measurement. However, as in the case of suspended solids, there is no correlation between turbidity and Secchi disc readings except in conditions of high turbidity. This fact is illustrated by Fig. 4-43, which presents the results of over 50 comparative measurements by Secchi disc and turbidimeter on waters of Suisun Bay and the Central Bay.

The greatest water clarity in terms of both Secchi disc reading and turbidity was recorded during October, before the first fall of rain had occurred. This is also the period of maximum water clarity in the Gulf of the Farallones, as explained previously. The lowest turbidity reading which could be found was 1.6 units, measured near Blossom Rock at slack before ebb on October 11, 1970. The highest Secchi disc reading was 10.0 ft, measured on a flood tide on October 6, 1970. All reported Secchi disc readings for Central Bay range between 0.6 and 10 ft. Summer and fall values are generally greater than 3 ft.

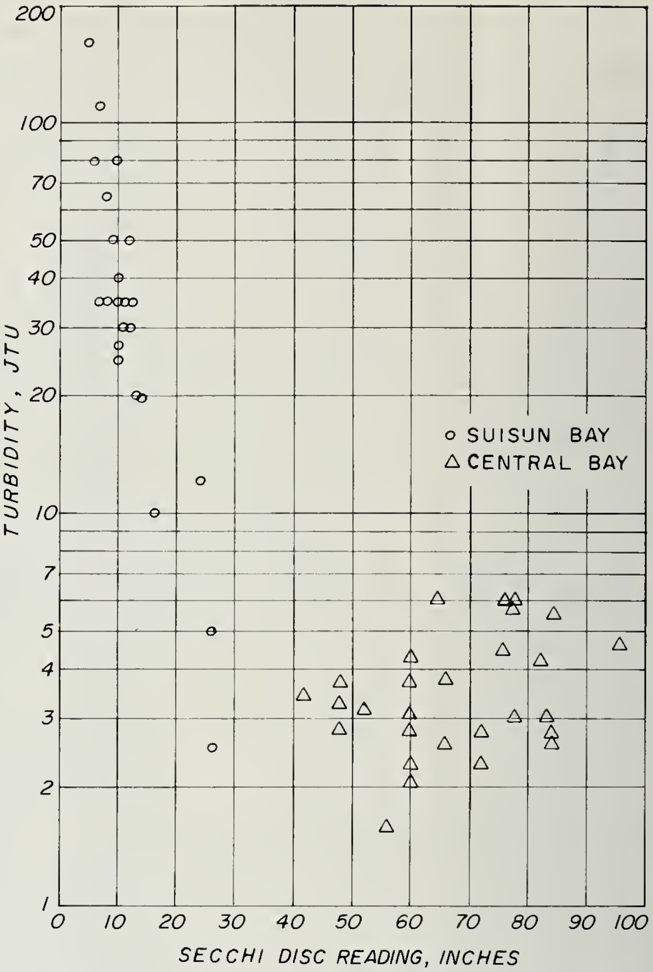


Fig. 4-43 Comparison of Turbidity and Secchi Disc Measurements - San Francisco Bay

Surface Drift

The data collected during this study on surface drift in San Francsico Bay were presented earlier together with the information on surface drift in the Gulf of the Farallones. Those findings are summarized here. Of 4,500 cardboard disc floats dropped in the Central Bay near Blossom Rock on June 16, 1970 at three different tidal conditions, not a single float was recovered either inside or outside the bay. On October 6 another 4,500 floats were dropped at approximately the same location in the Central Bay, again on three different tidal conditions. Only 16 floats were recovered inside the bay, though about 13 percent of the total released was recovered from the ocean beaches north and south of the Golden Gate.

Confirmation of the results of the surface drift studies was obtained from the massive oil spill mentioned previously, which occurred in January, 1971. On January 18 two oil tankers collided under the Golden Gate Bridge, resulting in damage which released several hundred thousand gallons of oil to the waters of the Central Bay. The ships were towed to a site near Angel Island, where the release continued for several hours.

The spill resulted in severe oil contamination of the ocean beaches from Duxbury Point to Point San Pedro, roughly the same area where the majority of floats were recovered in the surface drift studies associated with this report. Within the bay, however, oil contamination of the shoreline was confined to a small area adjacent to and seaward of the point of release. No oil was reported on the shoreline south of the Bay Bridge, north of Angel Island, or along the east shore of the bay. The oil spill thus confirms in dramatic fashion the results of the surface drift studies reported herein, which indicate that floatable material released within the Central Bay moves rapidly seaward without significant effect on the shoreline of the bay itself.

SPECIAL OCEANOGRAPHIC STUDIES

In addition to the studies of general oceanographic characteristics of San Francisco Bay and the Gulf of the Farallones reported previously, two special studies were undertaken. The first was a study of the performance of the city's two major outfalls at the North Point and Southeast water pollution control plants. The second involved the measurement of the amount of new water brought into the bay by the mechanism of tidal exchange.

Outfall Performance Studies

Submarine outfalls are designed on the basis of submerged jet theory, and their performance is normally measured by whether or not the receiving water meets established criteria. Receiving water quality control tests do not usually supply enough information to enable a quantative check on design theory. As a part of this study of the feasibility of marine waste disposal for the City of San Francisco tests were conducted on the city's two submarine outfalls to obtain a precise quantitative measure of the outfall performance. The results provided a check on the ability of outfall theory to predict accurately what the performance of an outfall will be.

Tests of field dilution were conducted on April 22 and 23, 1970 using the same basic procedure at both the Southeast and North Point outfalls. Rhodamine WT dye was metered into the effluent stream at the plant at a rate precisely proportional to flow, producing a constant concentration of dye in the effluent. The effluent field was then monitored by a boat equipped with a submersible sample pump and recording fluorometer, using the same techniques employed in the measurement of dispersion coefficients. Each test lasted for about 10 hours, and was timed to cover a full flood cycle plus the tidal reversal at each end. In this manner the effect of any concentration buildup due to the effluent field folding back upon itself was included in the measurements.

After the field dilution tests had been completed and evaluated, a further series of tests was undertaken in an attempt to correlate field dilution with field visibility. In this study aerial photographs of the effluent fields were compared with the dilution contours developed at the same tidal condition during the dilution tests, and Secchi disc profiles of the North Point effluent field were conducted to relate surface visibility to dilution.

North Point Dilution Study. The North Point effluent dilution test was conducted on April 22, 1970, spanning a flood tide with an amplitude of 5.2 ft. Dye was added to the effluent in a concentration of 0.15 ppm. The limit of detectability of dye on the recording fluorometer was about 0.15 ppb, which corresponded to a dilution of 1000 to 1.

At North Point, the effluent is discharged through four 48-in. cast iron outfall lines, two of which are suspended under Pier 33, and two under Pier 35. The lines terminate in 45-deg. downward elbows about 10 ft below the surface at the end of the pier. The boil caused by the surfacing effluent field is clearly visible at the pier ends, and to ensure that the maximum concentration was measured a technician was assigned to collect a grab sample directly from the boil at each pier every half-hour.

The results of the dilution study in terms of dilution contours at four different times in the test are presented in Fig. 4-44. The grab samples taken from the effluent boil showed that very little dilution is achieved by the time the effluent reaches the surface. Minimum dilutions in the boil ran about 3 or 4 to 1. However, within a distance of about 50 ft from the boil concentrations were reduced to the 20 to 1 range. Dilutions less than 30 to 1 were never encountered more than 600 ft from the end of the outfalls, and generally were contained within a radius of about 200 ft. On the flooding tide the effluent field trailed off to the east hugging the shoreline, as shown in Fig. 4-44 for the time interval 0732 to 1100. During this phase the 100 to 1 dilution contour encompassed a field about 2000 ft long. By the time the effluent field had traveled 6000 ft from the outfalls dilution exceeded the limit of detectability of the fluorometer, which was about 1000 to 1.

The slack tide period is illustrated for the time interval 1100 to 1245. During this period the detectable field expanded to its maximum dimensions, with the 100 to 1 contour encompassing a field approximately circular and about 3000 ft in diameter. The maximum dimension of the detectable field was about 7000ft.

As the ebb current developed after reversal, the detectable field and the area within the 100 to 1 dilution contour both decreased in size. This decrease illustrates the fact that dilution occurs so rapidly that there is no significant buildup as the field reverses. The most critical condition

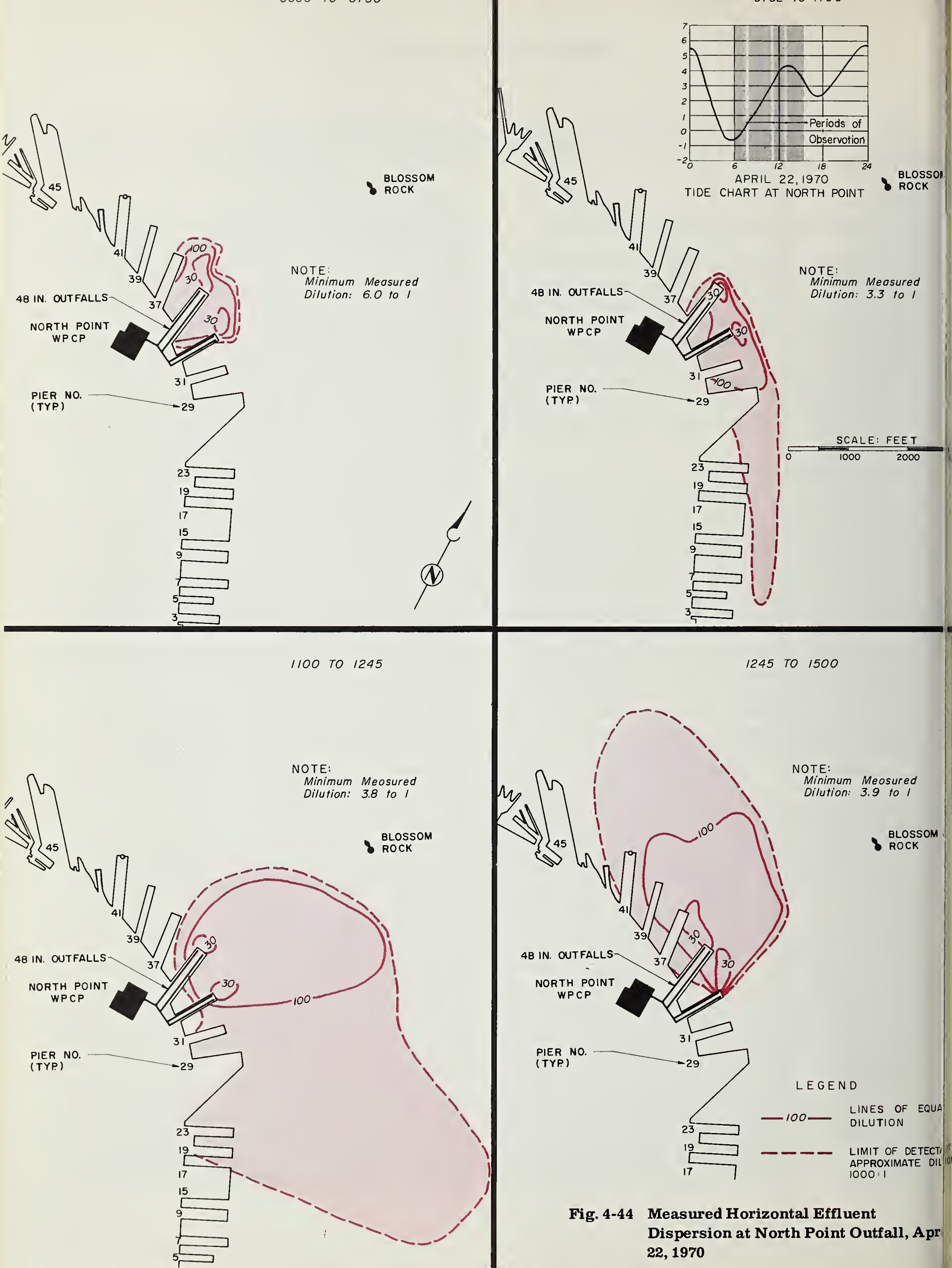


Fig. 4-44 Measured Horizontal Effluent Dispersion at North Point Outfall, Apr 22, 1970

therefore is at slack water, when the field of high concentration reaches its maximum size because advection is low.

Fig. 4-45 presents vertical profiles through the effluent field at various times during the test. Temperature and salinity profiles were also taken at the locations shown on Fig. 4-45, and these are presented in Volume 2, Data Supplement. The profiles of dye concentration show that the effluent field is most concentrated near the surface, but that it is mixed rapidly to substantially the full water depth. This is exactly the distribution that one would expect from a very large effluent flow and what amounts to a point release.

Southeast Dilution Study. The Southeast outfall dilution test was conducted on April 23, 1970, spanning a flood tide with an amplitude of 5.0 ft. The existing Southeast outfall has a submarine diffuser located about 500 ft offshore at a depth of approximately 40 ft. The diffuser is 300 ft in length and has 18 pairs of ports spaced at 16-ft intervals. The ports average about 5.1 inches in diameter. It was anticipated that initial dilution of the waste might be as great as 100 to 1, and the quantity of dye was adjusted to permit measurement of a subsequent dilution of 100 to 1. Dye was therefore added to the effluent stream to produce a concentration of 1.0 ppm. With a limit of detectability of about 0.1 ppb, this permitted measurement of dilutions as high as 10,000 to 1.

The field data permitted the construction of dilution contours for the effluent field at three time intervals (Fig 4-46). As the figure shows, the minimum dilution was measured at the time of reversal from flood to ebb as was the case at North Point. Minimum dilution was in excess of 100 to 1 at all times except during the slack water period, when a minimum dilution of 53 to 1 was measured.

On the flood tide the effluent field clung to the shoreline as it did at North Point. This phenomenon is undoubtedly the result of frictional drag of the shoreline on the water mass. By 1200 a steady state condition has been established for the maximum flood current, and the measurable field stretched over two miles south, past Hunters Point. The minimum measured dilution under the maximum current condition was 140 to 1, and after about one mile of travel the minimum dilution was 1000 to 1. At the limit of detectability, after slightly more than two miles of travel, the minimum dilution was 10,000 to 1.

As the tide reversed from flood to ebb the effluent field spread out and reached the maximum concentration for the period of measurement. Minimum dilution measured in the center of the surfacing field at reversal was 53 to 1. The reduction in dilution at reversal is due primarily to the reduction in current velocity. Dilution occurred so rapidly as the field moved away from the dischrage point that there was a negligible buildup in concentration as a result of the field folding back on itself.

Vertical profiles of effluent concentration at various times are shown in Fig. 4-47. Temperature and salinity profiles were also taken at the locations shown, and these are presented in Volume 2, Data Supplement. Three of the profiles show that the effluent field tended to form a surface layer, with the maximum concentrations occurring in the top 15 ft of the receiving water. The remaining two profiles show substantially uniform vertical mixing.

Measured vs. Predicted Performance. The steady state test at the Southeast outfall provided an opportunity to check predicted performance of a submarine diffuser against actual performance determined by field measurements. Both initial and subsequent dilution were checked in this manner.

As described in Chapter 3, a computer program was used in this study to predict initial dilution of effluent discharged through submarine diffusers. That program assumes no current is in the receiving water, a condition which is approached but not reached at slack tide. Applied to the Southeast outfall diffuser, the computer predicted an initial dilution of 40 to 1 under the flow conditions which prevailed during the field test. The minimum initial dilution measured in the field test was 53 to 1 at slack water, which is considered to be excellent confirmation of the accuracy of the computer program. At maximum flood current the minimum measured initial dilution was 140 to 1, indicating that the prevailing current of about 1.5 K increased initial dilution by roughly a factor of 3.

Subsequent dilution of the surface field was compared to that predicted from the dispersion coefficients derived for Central San Francisco Bay. At maximum flood current the 1000 to 1 dilution contour extended about a mile from the diffuser. With an initial dilution of 140 to 1, a subsequent dilution of 7 to 1 was required to achieve an overall dilution of 1000 to 1. At a current of 1.5 K the field would move a mile in about 0.7 hrs. Referring to Fig. 6-2, for an initial field width of 300 ft the predicted subsequent dilution in 0.7 hrs is 4 to 1. Since Fig. 6-2 ignores vertical diffusion, this may

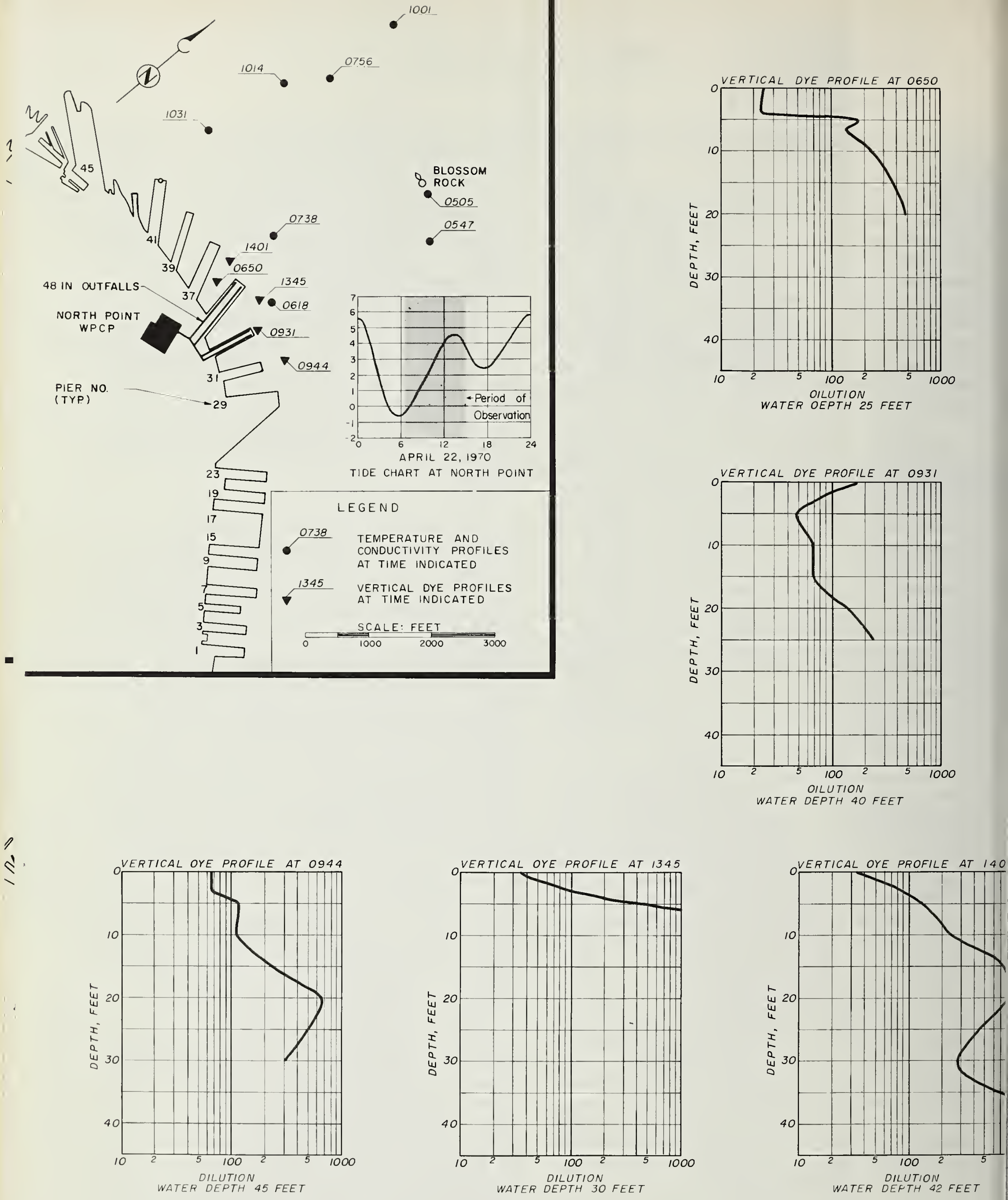
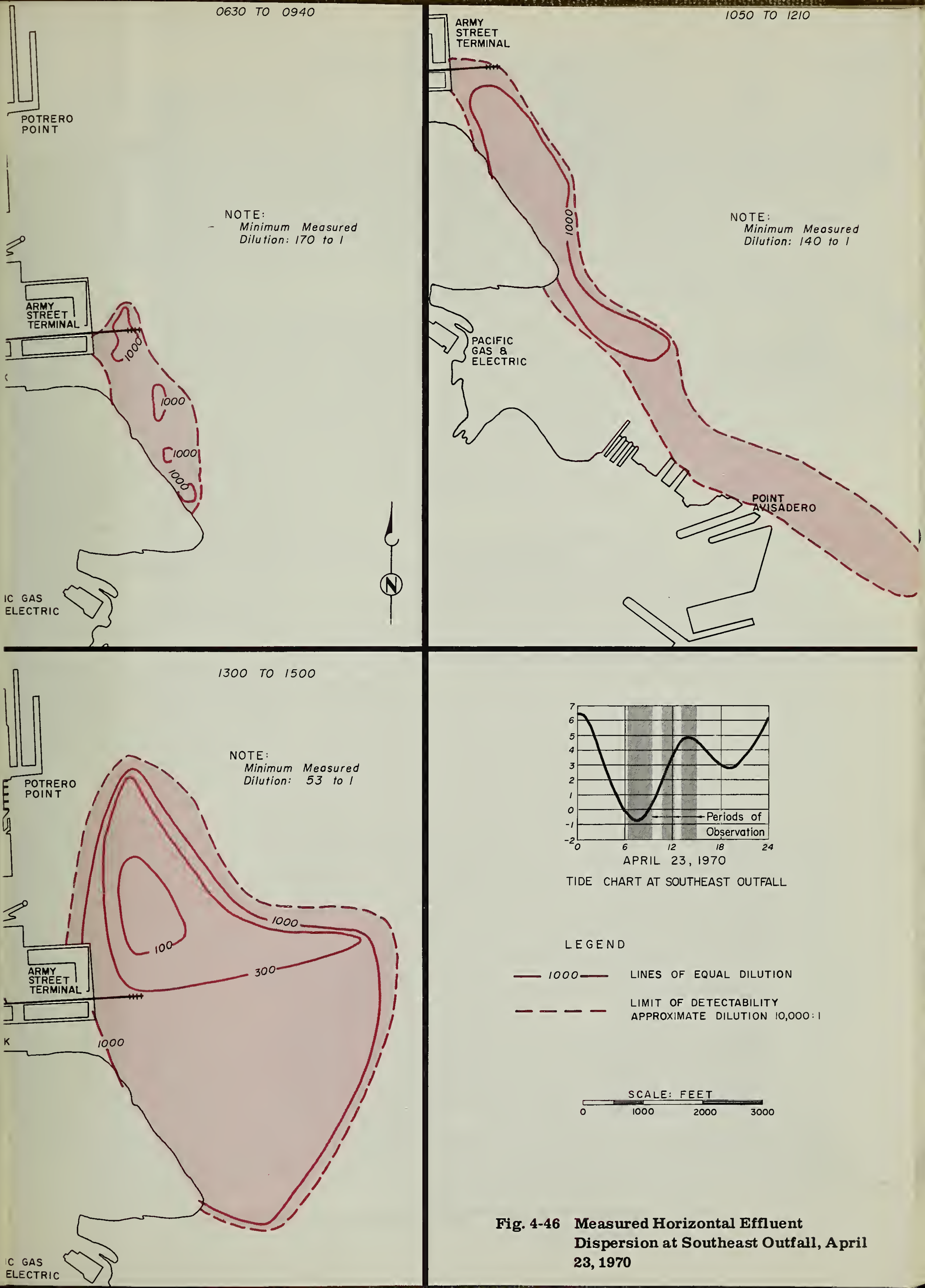


Fig. 4-45 Measured Vertical Effluent Dispersion at North Point Outfall April 22, 1970



NOTE:
Minimum Measured Dilution: 170 to 1

NOTE:
Minimum Measured Dilution: 140 to 1

NOTE:
Minimum Measured Dilution: 53 to 1

Fig. 4-46 Measured Horizontal Effluent Dispersion at Southeast Outfall, April 23, 1970

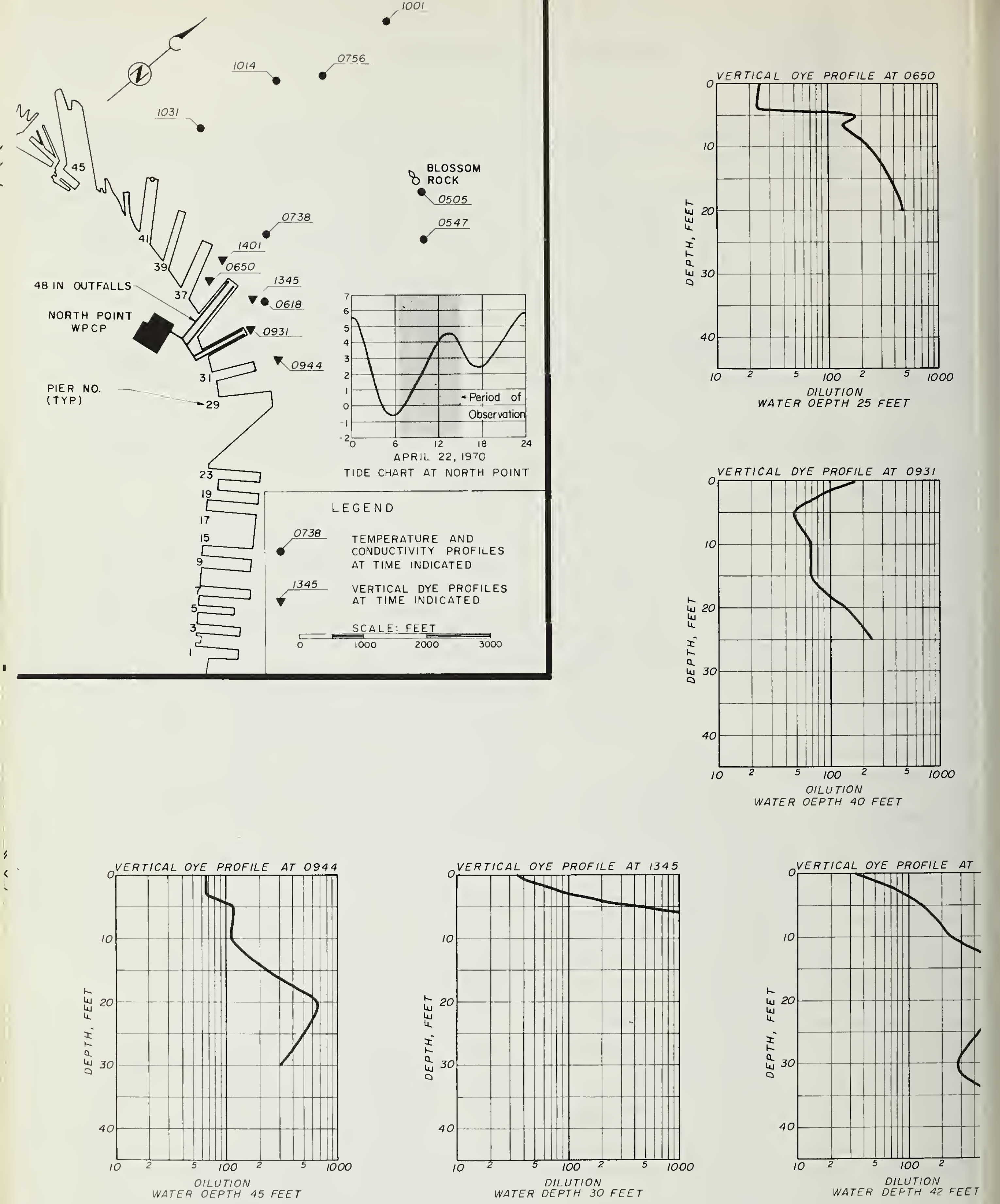


Fig. 4-45 **Measured Vertical Effluent Dispersion at North Point Outfall April 22, 1970**

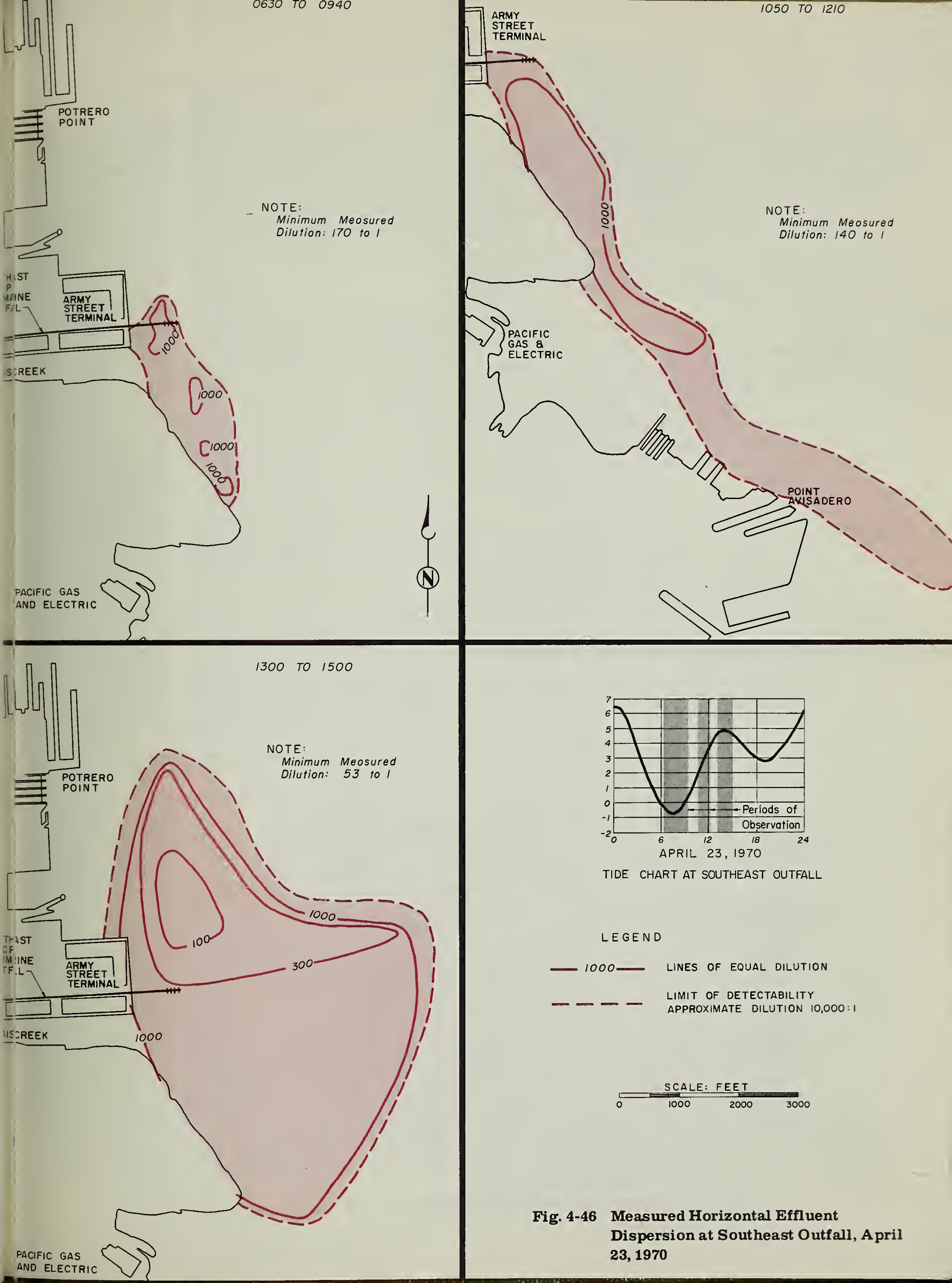


Fig. 4-46 **Measured Horizontal Effluent Dispersion at Southeast Outfall, April 23, 1970**

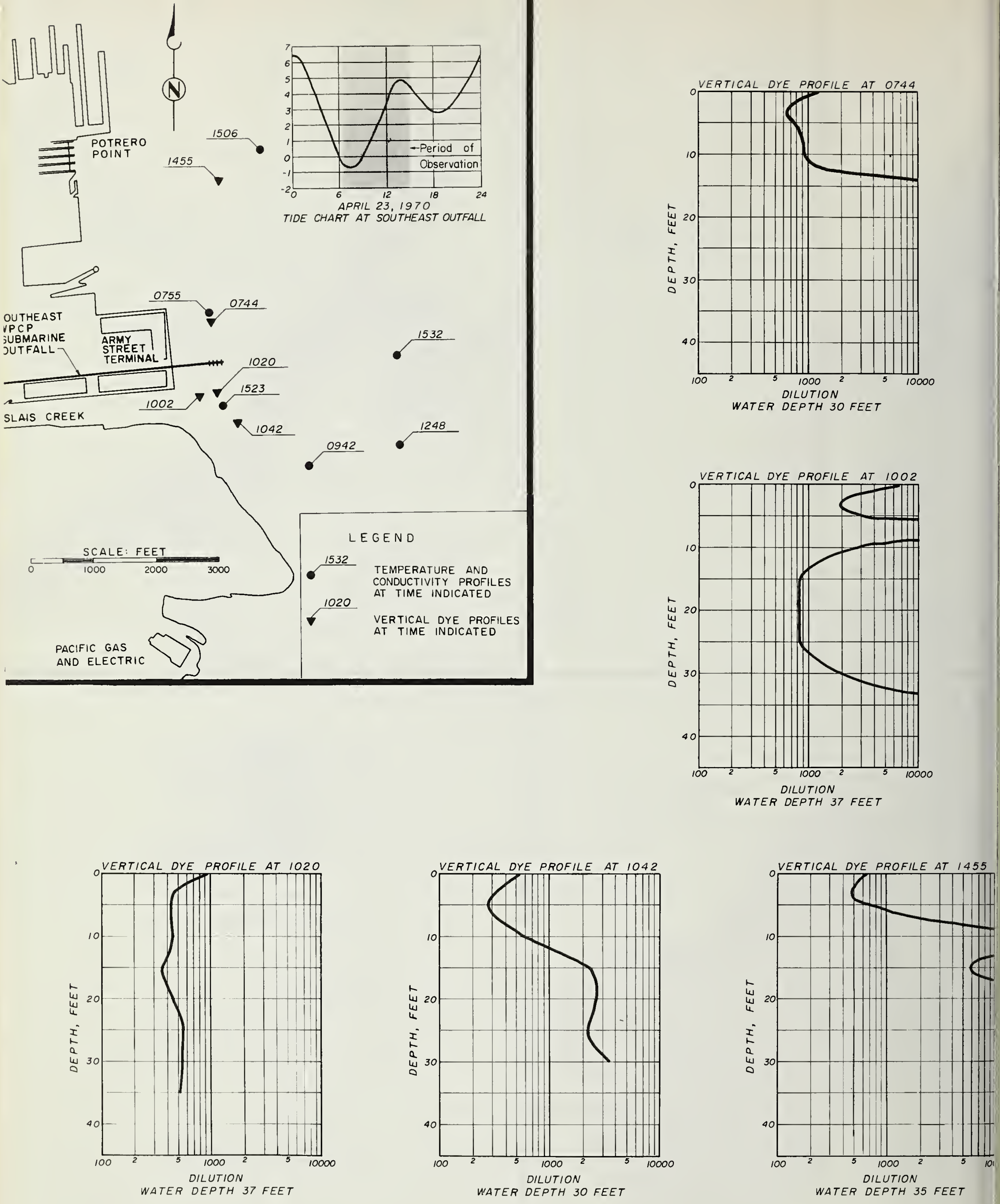


Fig. 4-47 Measured Vertical Effluent Dispersion at Southeast Outfall April 23, 1970

be considered a reasonable check on the validity of the curves developed for prediction of subsequent dilution. As a matter of fact, the curves quite probably give a conservative result because the measured dilution of the Southeast effluent field occurred along the shoreline where a boundary condition prevented dispersion of the field to the west.

Effluent Field Visibility. In establishing discharge requirements and water quality criteria the regulatory agencies have directed considerable effort toward control of the visible evidence of an effluent field. Field visibility is generally defined by the qualitative term "apparent color". However, a qualitative requirement is an enigma to the discharger who must determine methods and costs for meeting all requirements. An effort was therefore made in this study to define effluent field visibility in some quantitative or semi-quantitative terms. Starting with the results of the North Point and Southeast dilution studies, an attempt was made to relate effluent field visibility to dilution.

During the course of the study a number of aerial photographs were taken of the effluent fields at the North Point and Southeast water pollution control plants. From these photographs four were selected which corresponded approximately to the tidal conditions measured in connection with the dilution study. The extent of the visible effluent field was defined from the aerial photographs (Fig. 4-48), and the dilution contours from Figs. 4-44 and 4-46 for the comparable tidal condition were superimposed on the visible field. While admittedly imprecise, this method gives an indication of the probable dilution at the visible limits of the field. From Fig. 4-48 it can be seen that the visible field consistently extended beyond the 100 to 1 dilution contour, and in some cases appeared to approach or exceed the 1000 to 1 contour. From this information it was concluded that the primary effluent from the present North Point and Southeast water pollution control plants is visible in the receiving water in dilutions at least as great as 500 to 1.

In other phases of the oceanographic studies it was found that Secchi disc readings were directly related to visible water phenomena. Two sets of Secchi disc profiles through the North Point effluent field were therefore taken to aid in the assessment of field visibility (Fig. 4-49). The profiles on August 21 were taken at about slack water and the profiles on September 16 were taken near maximum ebb current.

The August 21 profiles define an effluent field with a width of about 2000 ft and a length of about 3500 ft. The east-west profile did not cover the full length of the field, because the Secchi disc reading at the west end of the profile was two ft less than at the east end. Relating these profiles to the dilution contours on Fig. 4-44, it appears that the Secchi disc was measuring a substantial difference in water clarity at dilutions in excess of 100 to 1.

The September 16 Secchi disc profiles on Fig. 4-49 measured a tidal condition comparable to that defined by aerial photography on June 17, 1970 (Fig. 4-48). In this case the east-west profile was run two miles west of the discharge site, and the end of the visible field was not reached. Referring to Fig. 4-48, it appears entirely probable that the visible field on that occasion extended to a dilution of 1000 to 1 or greater.

Tidal Exchange Measurement

One of the basic factors controlling water quality in the Central Bay is the exchange of bay and ocean waters which takes place due to tidal action through the Golden Gate. Not all of the water which ebbs from the bay returns to it. Some is transported away by ocean currents and replaced by new ocean water. Tidal exchange ratio, simply stated, is that portion of the flooding tide which is ocean water entering the bay for the first time. Tidal exchange can be a powerful flushing mechanism even when there is no net outflow from the San Francisco Bay system, and it therefore strongly influences the residence time of wastes in the Central Bay.

At about the time the City and County of San Francisco commissioned this study, the California State Department of Water Resources undertook a study of the waste assimilative capacity of San Francisco Bay using mathematical hydrodynamic and water quality models. The Department of Water Resources recognized the need for a reliable value for tidal exchange to be used in the models, and the two agencies agreed to cooperate in a special study to determine the tidal exchange ratio for San Francisco Bay. That study is presented as a separate report in Volume 2, Data Supplement. This section is a brief abstract and commentary on the tidal exchange study.

Tidal exchange was computed by measuring the chloride levels at the mouth of the Golden Gate on an ebbing tide and on the following flood tide and comparing these values with the chloride level in ocean water. The increased level of chlo-

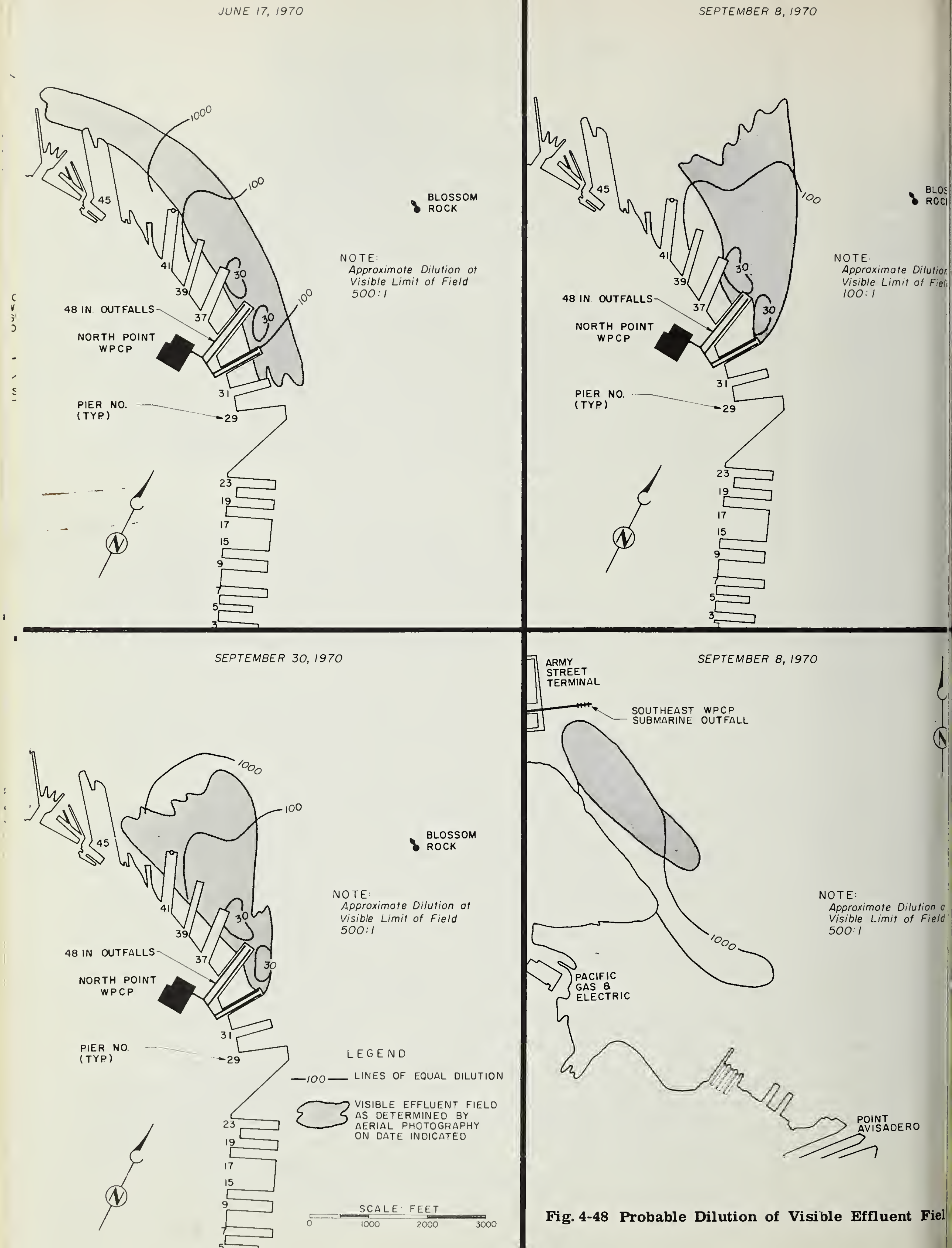
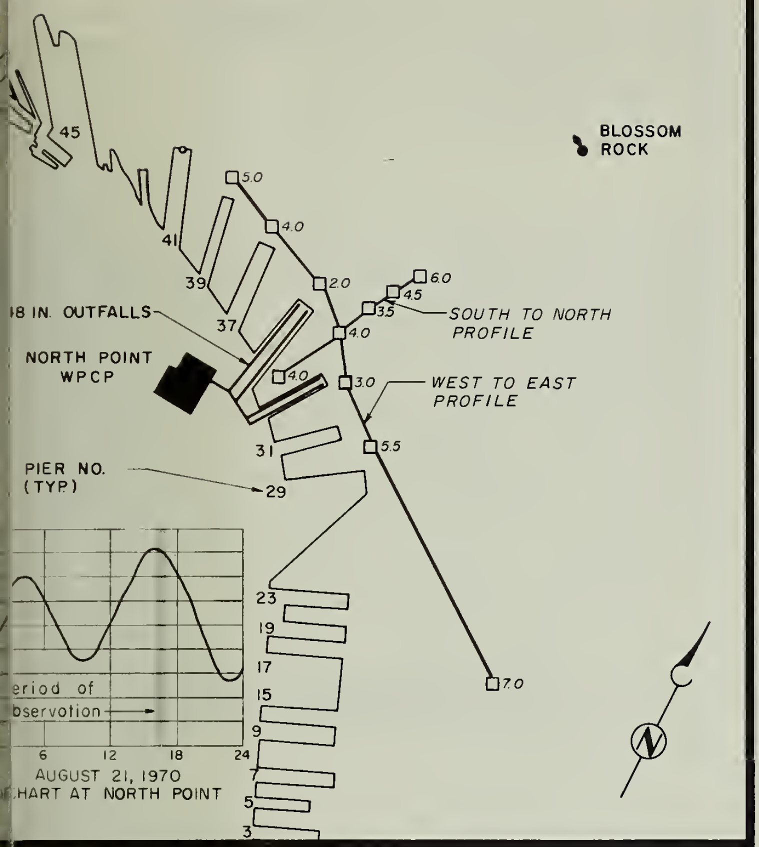
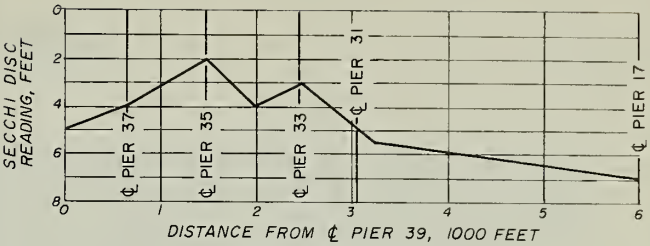


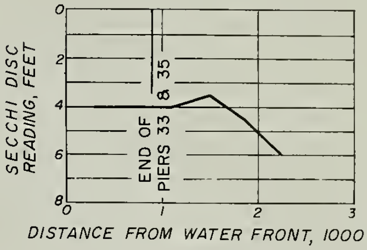
Fig. 4-48 Probable Dilution of Visible Effluent Fiel

AUGUST 21, 1970
1555 TO 1630



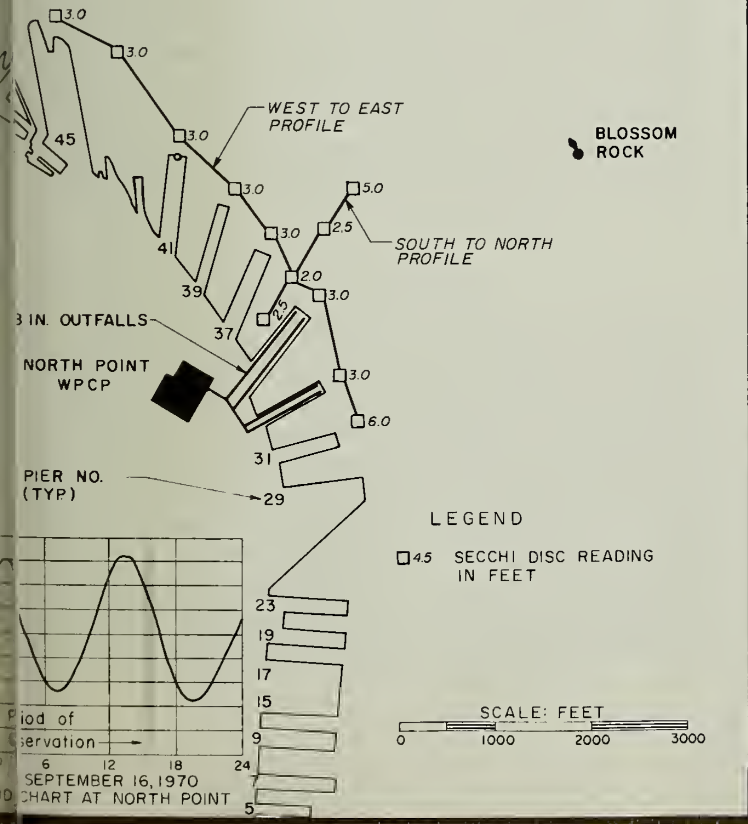


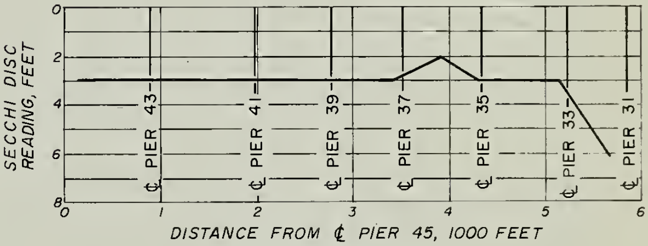
WEST TO EAST PROFILE
AUGUST 21, 1970



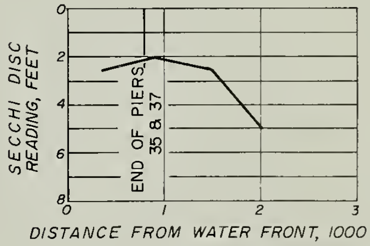
SOUTH TO NORTH PROFILE
AUGUST 21, 1970

SEPTEMBER 16, 1970
1505 TO 1540





WEST TO EAST PROFILE
SEPTEMBER 16, 1970



SOUTH TO NORTH PROFILE
SEPTEMBER 16, 1970

Fig. 4-49 Secchi Disc Profiles of North Point Effluent Field

rides on the flood tide, caused by new ocean water entering the bay, provided the basis for calculation of tidal exchange ratio.

Two cruises were conducted on days with tides of different amplitude. The results (Fig. 4-50) showed that tidal exchange ratio increases with the amplitude of the flood tide. For the median tidal amplitude of 4.1 ft, the tidal exchange ratio in dry weather is about 24 percent due to tidal flushing alone. Stratification of flow, such as occurs during periods of high fresh water runout through the bay system, results in a massive increase in the amount of tidal exchange. The wet weather value was not defined during this study, but it is believed by the authors to run at times in excess of 80 percent.

The value of 24 percent measured for average tidal exchange during dry weather brings approximately 24 billion cubic feet of new ocean water into the Central Bay during each 25-hr tidal cycle. Since this value is a function of tidal hydrodynamics, it is not influenced by the flow of fresh water through the bay system. Rather, any fresh water flow which results in significant stratification will serve to increase the measured values.

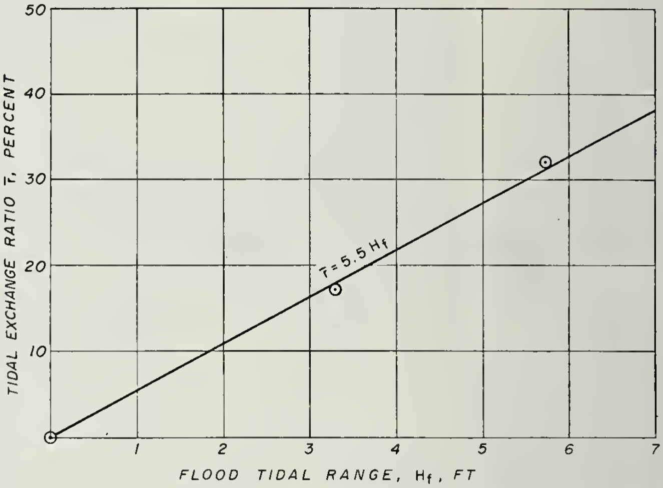


Fig. 4-50 Tidal Exchange Ratio versus Flood Tide Range for Dry Weather Conditions

CHAPTER 5

ECOLOGICAL INVESTIGATIONS

Ecology is defined as the study of the total relationship of an organism to its environment. In recent years, however, the definition of ecology has been modified by general usage to encompass all studies of conservation and environmental biology. At the same time, the necessity for environmental protection has become a major concern of an active and aware society. This concern has been expressed through increased expenditure of public funds for research and construction for pollution control. It has also produced a refinement of the methods of ecological investigation, and more importantly, a better understanding of the consequences of environmental stress.

When properly understood, the environment can be protected and still managed in such a way that man's interests and the conservation of nature are balanced. The environment is a regenerating resource, and, like other resources, it can be utilized to its fullest potential or it can be over-exploited. In many cases, unfortunately, the boundary line between utilization and exploitation has been determined by trial and error.

The fact that modern technology can influence the environment to a greater extent today than at any time in the past emphasizes the need for an ecological approach to many engineering studies. The problem of marine waste disposal is a prime example . The disposal of large volumes of sewage effluent to a marine environment creates a potential for large scale environmental change, and ecological investigations are essential to insure that detrimental changes will be avoided.

Objectives of the Ecological Program

The ecological phase of the marine study for the City and County of San Francisco had two principal objectives: (1) documentation of existing conditions at locations that might be influenced by a newly constructed submarine outfall; and (2) prediction of the ecological effect of disposing of large quantities of treated municipal sewage effluent in waters adjacent to San Francisco. The information developed for these two objectives, together with the results of the physical oceanographic program, provided the basic input for the development of an integrated long-range program for marine waste disposal.

Documentation of Existing Conditions. The investigation to gather information about existing conditions in the marine environment required field measurements covering the changing seasons for at least a full year. A year was considered the minimum time necessary to document the many chemical, physical and biological parameters of the environment which are in a constant state of change. Some of the measurements, such as sedimentation, may change very slowly, while others, such as plankton and fish populations, may change rapidly. A knowledge of these natural fluctuations aids not only in prediction of the environmental impact of a waste discharge, but also in identification of the causes of later environmental change. This separation of natural from man-induced fluctuations in the environment can only be made if the ranges of natural fluctuations have been previously documented. Finally, these data provide baseline information which can be used in the formation of a monitoring program for surveillance and continued research in the marine environment.

Prediction of the Effect of Waste Discharge. Determination of the effect of discharging liquid wastes into the marine environment involves not only knowledge of physics, chemistry and biology of water, but also the interaction between these disciplines. Often, subtle changes in the food chain, predator-prey relationships, ion balances or habitat availability are capable of causing significant change to the total environment; and these are but a few of the many interactions which are capable of influencing the environment. The impact may not always be deleterious. It may, in fact, have beneficial effects such as increasing the productivity of a commercially important species. In any case, however, the importance of the marine environment to man makes it imperative that changes not be left entirely to chance.

Scope of Work

The ecological research program was

designed to integrate a field investigation of the marine environment surrounding San Francisco with a laboratory investigation of the responses of selected marine organisms to dilutions of San Francisco composite sewage effluent. The integrated data from the completed investigations were then used to predict the effects of municipal waste discharge in the marine environment and to provide a basis for future monitoring.

The scope of work for the ecological program was developed during 1969 through discussions between Brown and Caldwell and the Department of Public Works of the City and County of San Francisco, with guidance from the Technical Advisory Board and important contributions from the California Department of Fish and Game. Dr. Wheeler North, a member of the Technical Advisory Board, was instrumental in establishing the scope of the research program and participated in many of the field investigations. Dr. Curtis Newcombe, also a member of the Technical Advisory Board, contributed much to the laboratory investigations by assisting in the design of the research program and making available laboratory space and graduate students for completion of the investigations.

The California Department of Fish and Game, speaking through the Project Advisory Board described in Chapter 1, emphasized the economic importance of the Dungeness crab, *Cancer magister*, to the fishery of San Francisco and proposed that a major part of the ecological program should be devoted to the study of the effects of waste discharge on this animal. The Department of Fish and Game further suggested that, as the larval stages of the Dungeness crab were most likely to be susceptible to effluent toxicity, an attempt should be made to study the entire life history of the Dungeness crab. Only in this way could assurance be made that a municipal waste discharge would not be detrimental to the species. The suggestions of the Department of Fish and Game were incorporated into the work program.

The initial work program consisted of a field investigation phase and a laboratory investigation phase. Each of these phases was divided into a detailed study of the Dungeness crab and a general study of other species. As the program developed, the laboratory investigations were expanded in time and scope at the recommendation of the Technical Advisory Board. The final work program for the laboratory investigations resulted in additional toxicity bioassays, blood studies and a biostimulation study.

Field Investigations. Field studies were conducted on a seasonal basis during 1970. Thirty-two days of cruises or shore field trips were undertaken in Central San Francisco Bay or in the Gulf of the Farallones. On these trips information was gathered from many different marine communities in an attempt to document existing populations and species distributions throughout the study area. The field study section of the ecological program included the following phases:

1. **Plankton studies.** The plankton study phase of the field investigation involved a search for Dungeness crab larvae and a general study of the total plankton community. Measurement of the abundance and distribution of larval Dungeness crabs within the Gulf of the Farallones was necessary to predict the influence that a waste discharge might have on this commercially important species. An analysis of the number and diversity of plankton samples also provided information about the spatial and seasonal productivity of the study area.
2. **Benthic studies.** The benthic sampling program was designed to identify the distinct bottom communities within the sampling area and to determine the distribution of juvenile and adult Dungeness crabs in the Gulf of the Farallones. Productivity estimates were also made for each benthic community.
3. **Diving studies.** Diving studies along the ocean coast were designed to measure the near shore benthic community and to gather base line data for future monitoring programs. Diving surveys were also used to reveal the effects of existing discharges on the marine environment.
4. **Intertidal studies.** Intertidal surveys were conducted in San Francisco Bay and along the ocean coast to obtain measurements of species diversities, productivities, and other parameters for future monitoring programs. Intertidal surveys were also used to assess the effect of existing effluent discharges.
5. **In-situ cage experiments.** Cage studies were performed in existing effluent fields in order to measure toxic effects of municipal waste discharges. Background toxicity associated with San Francisco Bay water was also studied.

In addition to the above phases of the work program, the field investigations were used to complement laboratory investigations by identifying the organisms that should be studied and by providing a supply of test animals.

Laboratory Investigations. Laboratory investigations were conducted during 1970 to study the effects of dilutions of composite San Francisco waste on a variety of organisms from the marine environment. The major emphasis of the research program involved acute and chronic toxicity studies on all life stages of the Dungeness crab. The remainder of the program consisted of testing the effect of dilutions of composite effluent on any marine species found in the study area which could be obtained in sufficient numbers for analysis. The following experimental designs were employed during the research program for long term and short term studies with larvae as well as adult organisms:

1. **Static bioassays.** These tests were mainly used for acute toxicity measurements with adult fish and invertebrates. Many dilutions were studied and an attempt was made to measure the TLm for each animal studied.
2. **Environmental chamber experiments.** A controlled environment chamber was used to study acute toxicity in invertebrate larvae. A major part of these tests studied the eggs and various larval stages of Dungeness crab in dilutions of composite effluent.
3. **Continuous-flow bioassays.** A method was developed for the continuous addition of dilution water and composite effluent into a test container. This apparatus was used to study short term and long term toxicity effects on Dungeness crab larvae. The continuous-flow system was employed because it most closely approximated the natural environment in a controlled experiment.
4. **Microcosm study.** Dungeness crabs were raised from larvae to adult form in various dilutions of composite sewage effluent in large model environments. This study measured long term toxicity effects on Dungeness crab growth in an environment with other interacting organisms.
5. **Blood studies.** The response of blood pigment distribution and number in three-spined stickleback was studied in various dilutions of municipal waste. This study was undertaken to measure the mechanism and magnitude of possible stress from dilutions of composite effluent which were not acutely toxic.
6. **Biostimulation investigation.** The response of algal growth to dilutions of composite municipal effluent was studied to predict the effect that nutrient additions might have on the marine environment.

THE SAN FRANCISCO ESTUARY

An estuary is a partially enclosed body of marine water such as a river mouth, lagoon, fjord or bay. This body of water is typically characterized by an area where fresh water from land runoff mixes with high salinity water from the ocean. It is this mixing of water masses and resultant fluctuations in salinity that are the main factors in determining the distribution and abundance of flora and fauna within the estuary. The adaptation to these salinity stresses by a variety of specialized organisms in the estuary produces an ecosystem quite unlike the adjacent fresh or marine environments. In this discussion the San Francisco estuary is defined as the San Francisco Bay system and the adjacent ocean waters which are influenced by its outflow.

Historically, the estuaries of the United States have played a major role in the development of America's economy, culture and way of life. Along the West Coast almost all urban centers have developed adjacent to major estuaries. In pioneer Western America it was the abundance of food in the bays and tidelands and the crossing of fresh water and marine transportation routes that proved to be the most important factor in the location of settlements. Since the turn of the century the spread of urban civilization has immensely increased the value of the estuary as a natural resource, particularly in the field of recreation and esthetic enjoyment. During the same period there has been a corresponding increase in the stresses upon the estuary due to waste discharges, industrial water use, dredging and filling, and similar activities. As with any natural resource, the maintenance of a proper balance between estuary conservation and exploitation requires an understanding of the physical, chemical and biological processes involved as well as intelligent management of the entire system.

The specific goal of this study is the development of recommendations regarding the marine disposal of sewage effluents from the City of San Francisco. However, an understanding of the characteristics of estuaries and the role they play in the marine ecosystem as a whole is necessary in order to place this study in its proper context. The following sections therefore describe the classical physical, chemical and ecological characteristics of estuaries and summarize the marine resources of the San Francisco estuary as reported by other investigators.

Physical and Chemical Characteristics of Estuaries

Chemical and physical characteristics of an estuary play a prominent role in affecting the type, abundance and distribution of organisms within the marine environment. To better understand the magnitude and scope of some of these influences, a classical description of the ecology of estuaries is presented. An understanding of the abiotic influences in an estuary is essential if we are to recognize the forces that are most important in influencing the biota of the San Francisco estuary and predict the changes that will result in the system from modifications of the chemical and physical environment.

The three most important factors operating to produce currents in estuaries are oceanic tides, stream flow and wind. The interaction of these forces often produces a complex system of water movements which is further modified by the morphology of the estuary basin and stream channel. The resultant currents and water characteristics are largely responsible for the distribution and nature of the estuarine biota.

Fig. 5-1 is a schematic presentation of current flow along the central axis of a hypothetical estuary. Theoretically, water circulation in an estuary is stratified, with deeper waters being more saline while surface currents contain a high proportion of fresh water. This stratification results from the fact that oceanic waters are typically denser than fresh waters.

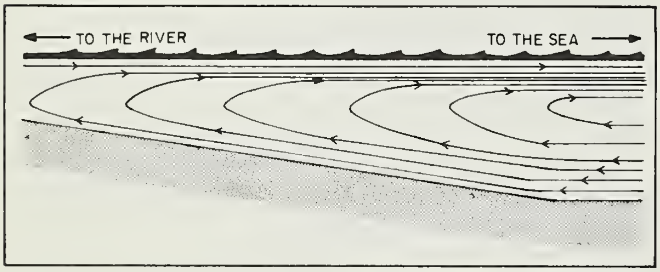


Fig. 5-1 Schematic Presentation of Current Flow Pattern Along the Central Axis of a Hypothetical Estuary.
Source: Reference 77 (Appendix A)

The presence of stratification within an estuary can exert profound effects upon the nature of the substrate, turbidity and biota. Where the bottom waters contain a high proportion of saline water, the benthos many miles inland typically reflects the marine environment. In the other direction, the surface layer of fresh water may extend many miles seaward and contain many typically fresh water organisms. The organisms are also restricted by the extreme temperature differences that may be associated with this stratification. The substrate and turbidity of the waters will also be influenced by stratification. Suspended material in fresh water runoff may be transported far to sea within the rapidly moving surface water layer before it settles.

In most estuaries, including San Francisco Bay, the classical stratification of fresh and marine waters is significantly altered by tides, wind and basin morphology. Vertical mixing produces regions of intermediate salinity. It is also common for stream flow to be held back and often reversed by a strong flood tide. Because of the opposing current systems (tide vs stream flow), flood tide current velocity is normally slow, while on an ebb tide current velocity is increased. Both the slow flood tide period, during which mixing is intensified, and the rapid ebb tide significantly affect the biota in four ways. First, the biota in mixed estuaries is more commonly subject to irregular changes in salinity than the biota in a stratified estuary. This is particularly true of benthic organisms that receive the full range of salinity variations. Second, the rapid ebb currents require that benthic organisms be well attached to the substrate in order not to be swept from the area. Third, the mixing of fresh and salt waters often makes available for nutrition, organic and inorganic substances in forms not regularly found in fresh or saline water alone. The chemical and physical processes of chelation and adsorption often play important roles in the releasing or trapping of nutrients and metals when river and ocean water mix. Finally, mixing of water layers often will allow settling of suspended material that normally would be washed out to sea in the surface fresh water wedge.

Basin morphology also contributes to mixing and sediment transport within an estuary. In a wide, unrestricted estuary, currents are typically slow, without significant turbulence. In a narrow, deep estuary, or in an estuary with a restricted mouth, rapid turbulent currents frequently occur which promote mixing. As the cross-sectional velocity of an estuary is not constant, the shape of the basin also influences sediment transport. An area of maximum velocity usually exists near the surface in the middle of the estuary channel. Near the shore, shallow waters typically have the slowest flow. This minimal velocity near the shore allows the deposition of suspended material and a warming of the shallow waters. The shallow nearshore waters then typically exhibit a different biotic community than the deeper, rapid moving water of mid-channel.

Wind and wave action also contribute to mixing and current patterns within the estuary. Wind effects are most significant in large shallow areas where they may serve to increase either tidal movement or stream flow depending upon the direction and intensity of the moving air mass. In estuaries where a long fetch (distance over which the wind can act) is present a strong wind can produce sizeable waves which act to mix the water mass and scour sediments from the bottom.

Estuaries exhibit areas of erosion, transport and deposition of sediments. Each of these processes, as well as the types of sediment involved, greatly influences the biota of the estuary. At the upper reaches of an estuary, current velocities are characteristically high due to fresh water inflow. This is particularly true during periods of high rainfall. In this area the erosive currents pick up vast amounts of sediment. As the bottom is very unstable, benthic organisms in this area are severely limited. The phenomenon of sediment transport can also occur at the estuary mouth due to fluctuating tidal currents. In this region, as in the upper estuary, unstable bottom conditions also limit the distribution and abundance of benthos.

The middle estuary typically is the region of sediment transport. Large quantities of material in suspension may restrict the penetration of sunlight and consequently limit the growth of rooted aquatic plants and phytoplankton.

Shallow waters at the shoreline and near the mouth of the estuary typically are areas of sediment deposition. The shores of estuaries are composed mainly of settled silt, sand and mud in varying proportions and degrees of compaction. Near the mouth of the estuary the intertidal zone and bottom substrate is usually made up of deposited sand. Marked zonation from sandy shores of the seaward slope to the mudflats or tidal marshes of the middle and upper bay is typical of most estuaries. In the areas of high deposition the benthos must be mobile if it is to survive being buried, while in other areas more permanent forms may be prevalent.

The type of the substrate is also known to exert a considerable influence on the plant and animal inhabitants of the estuary floor and shore. Both pure sand and pure mud present problems in the maintenance of living organisms. Pure sand substrates are difficult for burrowing organisms that must maintain an open burrow for feeding or respiration. Pure sand also is a poor substrate for rooted vegetation and other organisms that require a firm foundation. Sand is also typically nutrient poor. Pure mud substrates present problems of gill clogging, turbidity resulting in little light penetration, and a low oxygen tension beneath the surface due to a typically high sediment BOD. It has also been demonstrated that certain bottom sediments tend to hold saline waters as the tide ebbs and therefore extend the range of bottom-dwelling plants and animals that require high salinities.

The composition and activity of chemical substances within an estuary represents the end result of the mixing of two dissimilar water masses – those of the ocean and fresh water streams. The relative constancy of constituents in sea water (Table 5-1) is contrasted by wide variety of ion concentrations and ratios that can exist in fresh water. The mixing of these two disimilar water masses creates an environment whose chemical makeup is often completely different from either of the original waters. The interaction of chemical constituents through chelation, precipitation, adsorption and other ion interactions may produce an environment which supports a unique collection of plants and animals.

Whereas sea water generally has a higher dissolved solids concentration than the fresh water it mixes with in the estuary, fresh water typically is higher in nutrients and certain other constituents. The mixing of high salinity, nutrient poor waters with low salinity, high nutrient waters frequently results in the formation of highly productive ecosystems. In fact certain warm water

Table 5-1 Percentage Composition of the Major Ions of Two Streams and Sea Water

Ion	Delaware River at Lambertville, N. J.	Rio Grande at Laredo, Texas	Sea water
Na	6.70	14.78	30.4
K	1.46	.85	1.1
Ca	17.49	13.73	1.16
Mg	4.81	3.03	3.7
Cl	4.23	21.65	55.2
SO_4	17.49	30.10	7.7
CO_3	32.95	11.55	+HCO_3 0.35

estuaries such as the turtle grass community qualify among the most productive systems on the earth.[68]

The interaction of two water masses within the estuary produces a system that is unique. The estuary is not simply a mid-point between salt and fresh water, but rather is a complex system of physical, chemical and biological interactions which makes environmental management difficult. In addition, superimposed upon this system are diurnal and seasonal fluctuations, which constantly change the estuary and make it one of the most stressed of earth's ecosystems. For those organisms which have adapted, however, it produces a richness beyond compare in the biosphere.

Ecological Interactions of Estuaries

The estuary is a complicated system of actions and reactions among the biota as well as the physical and chemical environment. Fig. 5-2 presents energy flow through a simplified bay ecosystem. The figure illustrates the complex interaction between various trophic levels within an estuary and depicts the relative loss of organic matter throughout the food chain. It can be seen that it takes approximately 1.4 x 10^5 (42/0.0003) as much fixed organic matter to produce one gram of a marine mammal as it does to produce one gram of algae. The importance of the primary producers (phytoplankton) and of nutrient regeneration is evident in the functioning of a well balanced system. It is within these two levels that most organic matter is cycled within an estuary. The zooplankton and bacteria also form a vital link in flow of energy throughout the system, for it is from zooplankton that most carnivores and filter feeders receive their protein. Major other storehouses of food energy within the estuary ecosystem are found in the shallow water vegetation and bottom sediments.

Fig. 5-2 also depicts the major pathways through which man can influence the estuary directly or through his effluents. As the figure shows, man directly or indirectly influences all components of the estuarine community. The magnitude of man's influence upon the estuary varies from practically zero in isolated waters to many times the total normal organic load in stressed mismanaged systems. The subtle interactions between components of the estuary and man's possible impact demonstrate that proper management requires an adequate understanding both of the estuarine system and of man's influence upon it.

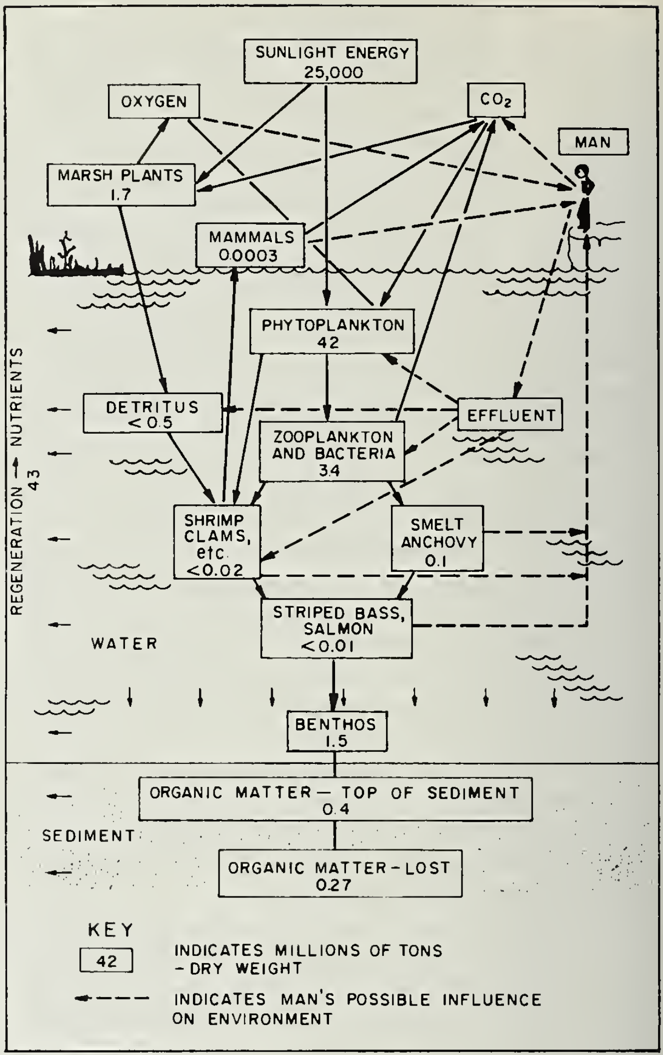

SUNLIGHT ENERGY 25,000
OXYGEN
CO₂
MAN
MARSH PLANTS 1.7
MAMMALS 0.0003
PHYTOPLANKTON 42
REGENERATION → NUTRIENTS 43
DETRITUS <0.5
EFFLUENT
ZOOPLANKTON AND BACTERIA 3.4
SHRIMP CLAMS, etc. <0.02
SMELT ANCHOVY 0.1
STRIPED BASS, SALMON <0.01
WATER
BENTHOS 1.5
ORGANIC MATTER — TOP OF SEDIMENT 0.4
SEDIMENT
ORGANIC MATTER - LOST 0.27
KEY
42 INDICATES MILLIONS OF TONS - DRY WEIGHT
INDICATES MAN'S POSSIBLE INFLUENCE ON ENVIRONMENT

Fig. 5-2 Energy Flow Through A Typical Estuarine Ecosystem.
Source: Reference 49 & 56 (Appendix A)

Whereas Fig. 5-2 illustrates the levels at which man's effluents can affect the estuarine community, Fig. 5-3 presents the various processes which will affect the ultimate distribution of the effluent. The conditions of dilution and transportation are favorable to the disposal of liquid wastes to the estuarine environment, while the processes of concentration are unfavorable.

Nature has a vast capacity to recover from minor modifications of the water environment by man. Too often, however, this capacity has created a false sense of security which is only revealed after extensive damage has been done to the environment. Fortunately, the damage is rarely irreversible. An understanding of the ecological interactions within the estuarine environment and the role of waste discharges in those interactions

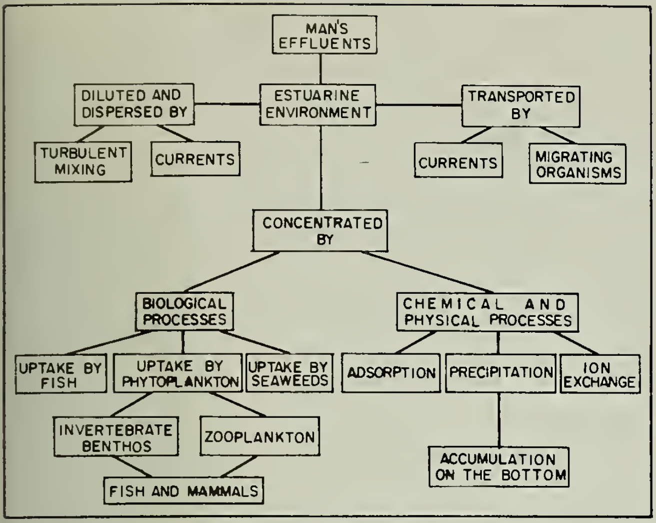


Fig. 5-3 Processes Which Determine the Fate and Distribution of an Effluent in the Marine Environment.
Source: Reference 58 (Appendix A)

was the goal of this study. Graphically illustrated, this study was concerned with the measurement of the intensity and direction of the major pathways in Fig. 5-2 and a study of the various mechanisms in Fig. 5-3 as they could relate to a municipal waste discharge within the marine environment surrounding San Francisco.

San Francisco Marine Resources

Broadly speaking, a marine resource is any factor in the marine environment which contributes to the total productivity, commercial value or esthetic enjoyment of the system. A resource may be biological, as in the case of the commercially valuable market crab; chemical, such as the nutrients which enhance the productivity of the waters; or physical, such as the scenic attraction of a clean beach with blue and white surf. For this report, discussion is confined to biological resources.

The results of previous investigations of the marine environment surrounding San Francisco were reviewed during the devlopment of the present research program. Biological, chemical and physical data available from previous studies influenced the scope of both the field and laboratory investigations described herein. Investigations near outfalls in Southern California were particularly useful in the development of sampling techniques and in a prediction of the needed scope of future monitoring programs in the San Francisco area.[34–44]

The majority of ecological investigations within the San Francisco estuary have been conducted in San Francisco Bay. Little has been reported on the ecology of the nearshore Gulf of the Farallones.

Biological resources may be divided for discussion into groups which are loosely identified by their place in the food chain. These groups are (1) the plankton, consisting of small floating or weakly swimming animal and plant organisms; (2) the benthos, which are bottom-dwelling organisms; (3) the fin fisheries; and (4) the intertidal wildlife. Resources related to the physical aquatic environment and adjacent land are discussed as they relate to the biota. The Dungeness crab fishery, which holds special significance for the San Francisco area, is discussed in a later section of this chapter.

Plankton. The value of plankton as a marine resource can hardly be overestimated, Phytoplankton, the tiny floating algae and diatoms, constitute the principal source of oxygen within the marine environment. In fact, it has been estimated that marine phytoplankton is responsible for up to 70 percent of the total oxygen found in the earth's atmosphere.[45] Phytoplankton also constitutes a food source for many organisms on higher levels of the food chain.

Zooplankton also qualifies as a major resource in the marine environment. Zooplankters are usually grazers, feeding on the phytoplankton, and are recognized as being at the base of the food chain for almost all aquatic organisms. Particularly important within the zooplankton are the copepods (minute crustaceans), which compose the largest food resource in the oceans of the world.

Fluctuations in diversity of microplankton and major zooplankton for Central San Francisco Bay are shown in Fig. 5-4. Microplankton include all phytoplankton and a limited number of very small zooplankters. The information presented in this figure was obtained by Dr. Erman A. Pearson from six sampling stations in Central San Francisco Bay from June 1963 through June 1964.[46] Dr. Pearson observed that there appeared to be a slight seasonal pattern associated with both micro and zooplankton. Lowest diversities for microplankton generally occurred in the spring, while minimum zooplankton diversity occurred during the late fall and winter. The period of low microplankton diversity was also found to correspond to the period of highest numbers. This inverse relationship is most likely the result of a pulse of one or two species which unbalances the population

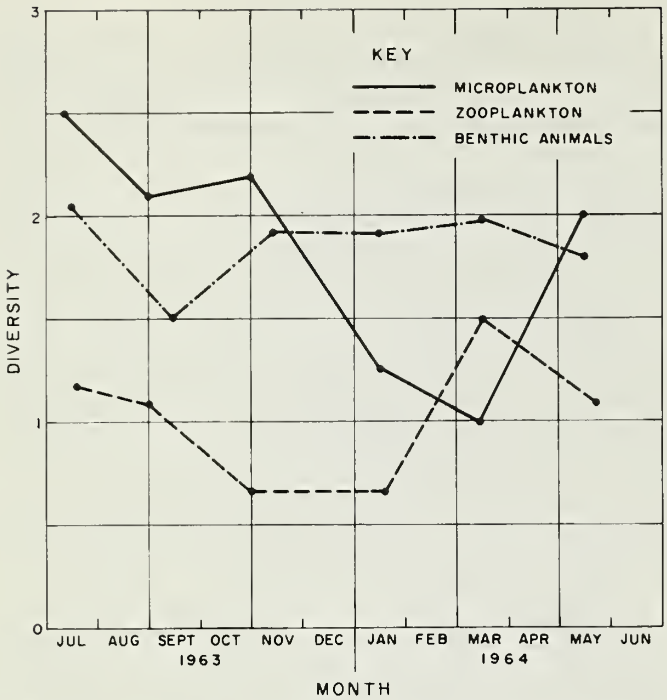


Fig. 5-4 **Seasonal Variation of Microplankton, Zooplankton and Benthos in Central San Francisco Bay**
Source: Reference 1 (Appendix A)

and contributes to a decrease in the diversity index. Low diversity in the microplankton was further observed to correspond with periods of highest river outflow. Presumably, increases in fresh water could flush out or restrict more traditionally marine species. The most numerous members of the microplankton were diatoms, which occasionally exceeded one million cells per liter.

The calculated diversity of the zooplankton was usually less than the diversity of the microplankton. This was due to the extremely large numbers of a relatively few species of copepods. J. A. Aplin[47] also reported that the most numerous members of the zooplankton from San Francisco Bay were copepods. Both Aplin and C. G. Esterly,[48] who studied copepods collected by the U. S. Bureau of Fisheries, reported that copepods of the genus, *Paralabidocera*, were the most abundant animals in San Francisco Bay.

A study of oxygen production and utilization within the water column was conducted at two stations within the Gulf of the Farallones during 1970 by Brown and Caldwell. Station A (Fig. 4-27) was located nearshore and was typically exposed to bay water outflow, while Station B was situated further from shore and more nearly represented coastal ocean water. Each station was occupied for 24 hours, and a continuous record of surface (one meter) temperature, dissolved oxygen, Secchi disc and percent oxygen saturation are plotted in Fig. 5-5.

The most evident feature of Fig. 5-5 is the higher dissolved oxygen concentrations at Station B as compared to Station A. Coincident with the higher oxygen levels at Station B is greater water clarity. Only when the transparency of the water was reduced at Station B did dissolved oxygen production decrease to the levels found at Station A. It was found that the reduction of Secchi disc readings, and corresponding lower dissolved oxygen levels at Station B, occurred during a period of strong ebb flow from the Golden Gate which brought more turbid water to the station. As Station A was situated at all times within the surface plume from the Golden Gate, the Secchi disc readings at this station remained comparatively low and constant during the sampling period. The average of Secchi disc readings at Station A was 12.2 ft. Station B Secchi disc readings fluctuated widely as the edge of the fresh water plume passed by the station . When Station B was in clear oceanic water the average Secchi disc transparency was 23.5 ft, and when the station was in the fresh water plume Secchi disc readings were similar to Station A.

The oxygen production throughout the day at Station B was distinctly higher than the values at Station A. If the turbid plume from the Golden Gate had not passed Station B the production would have been still higher. Nearshore ocean waters (Station B) generally have lower nutrient levels than the bay waters (Station A), but they do not have the associated high turbidities. This lower turbidity allows deep light penetration, a deeper photosynthetic zone and consequently higher total oxygen production. This phenomenon of reduced productivity where turbidity limits light penetration was given by Krone[50] as the mechanism which prevents algal blooms within San Francisco Bay.

The biostimulation capability of San Francisco Bay water was studied by Engineering Science, Inc. for the San Francisco Bay-Delta Water Quality Control Program in 1968.[51] The results of their laboratory findings for Central San Francisco Bay are graphed in Fig. 5-6. In these experiments the growth rate of the marine diatom, *Navicula*, was studied in various test media under varying nitrate concentrations. The diatom was grown in ASP-2 (an artificial growth medium), bay water with sodium nitrate, and bay water with an activated

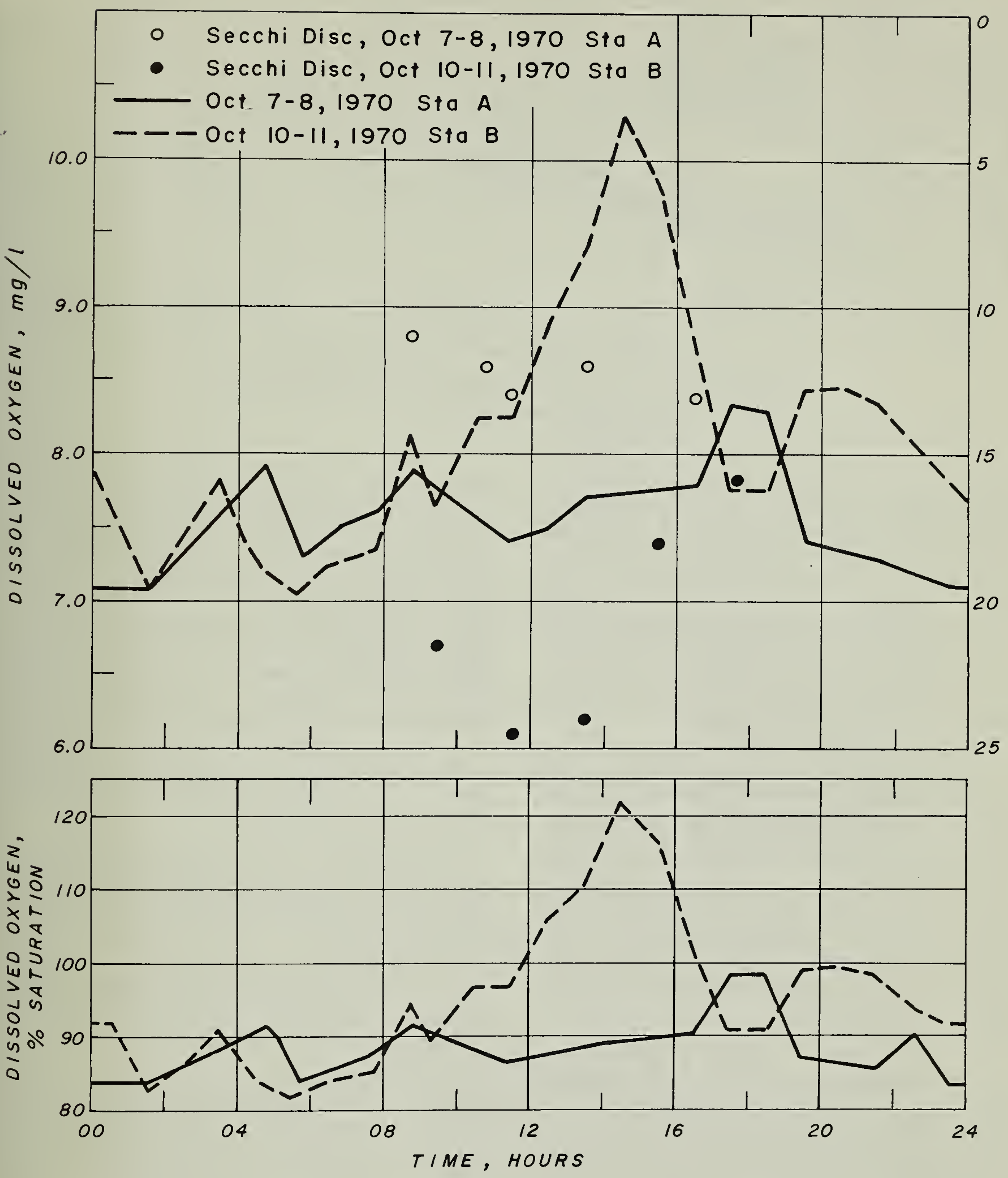


Fig. 5-5 **Oxygen Production at Two Stations in the Gulf of the Farallones**

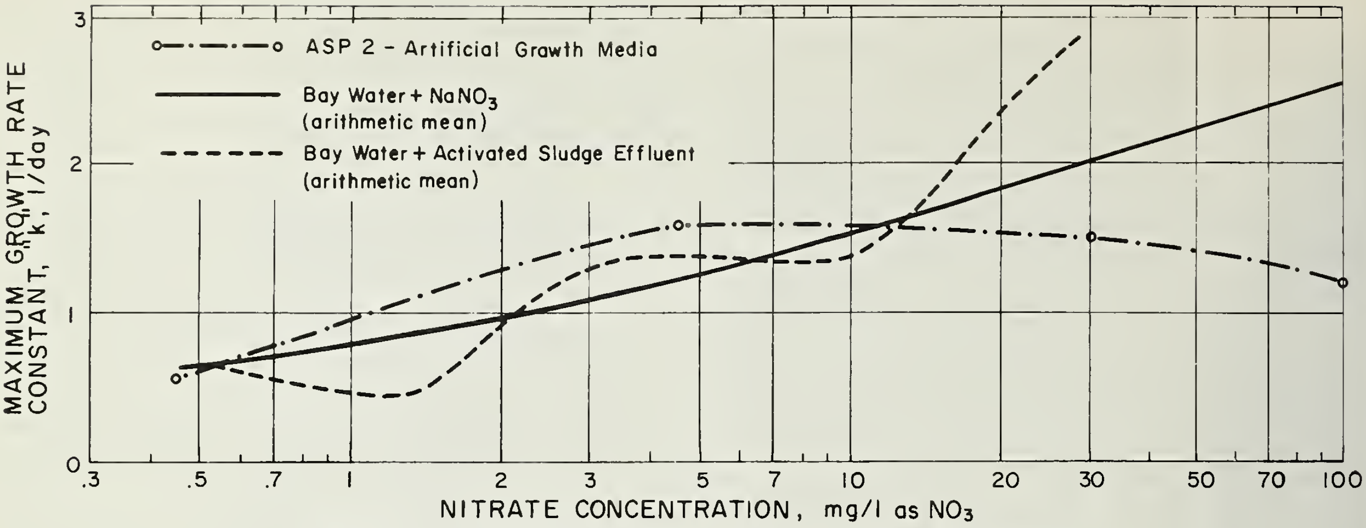


Fig 5-6 **Growth Stimulation in Central San Francisco Bay**
Source: Reference 51 (Appendix A)

sludge effluent. The growth rates (k) for *Navicula* in the three test solutions increased moderately with increased nitrate concentration up to approximately ten milligrams per liter, where the three curves diverged. Above this nitrate concentration both bay water test media had a higher growth rate than the ASP-2 medium. The results of this study indicated, however, that at the normal nitrate concentrations found within San Francisco Bay no stimulation would be expected from the addition of an activated sludge effluent.

Benthos. Fluctuations in the diversity index for the benthos of Central San Francisco Bay are illustrated in Fig. 5-4. Because many benthic animals are permanently anchored at the bottom or are mobile only within the sediments, the diversity index frequently does not change much during a year's study. Such was the case with benthic diversity measured in Central San Francisco Bay during 1963-4. Changes in benthic diversity would be more common in areas of large bottom changes, extreme seasonal stress or large changes in predator populations.

A list of benthic organisms collected by orange peel dredging and beam trawl sampling in Central San Francisco Bay was compiled by J. A. Aplin in 1967.[47] Of the approximately 100 species listed, the most abundant species was the clam, *Gemma gemma*. In two cases over 2000 individuals were present in a single sample.

Information on the benthos of the nearshore Gulf of the Farallones is quite limited. One study in the area of interest was that of Ebert and Cordier[52] who conducted a combined trawl, trapping and diving study during 1966 in the area of the Seal Rock dredge spoil disposal site (Fig. 5-7). Moderate currents and poor water visibility severely limited the diving program. The investigators did find as "extreme paucity of organisms" in the study area and attributed this to the very unstable and shifting sand bottom. Crab trapping yielded 564 mature adult and 39 juvenile Dungeness crabs. The presence of the juvenile crabs within the fish trawls indicated to the authors that this area was a "crab nursery ground". The life history and economic importance of Dungeness crab to the San Francisco area is discussed in a following section of this chapter.

Fin Fisheries. The California Department of Fish and Game[53] divides the commercial fin fisheries of the San Francisco area into two major groups:

1. **The pelagic fishes.** This group contains fish normally associated with the water column (pelagic). Examples of the pelagic fishes are albacore, herring and anchovies.

2. **The stable group.** This fishery is mainly composed of bottom dwelling organisms that are primarily harvested by trawling. Salmon, an important semi-pelagic fish, is included in the stable group. Other members of this group are the soles, flounder and rockfish. This division allows an examination of major fishing techniques and commercial effort for the total San Francisco area fisheries.

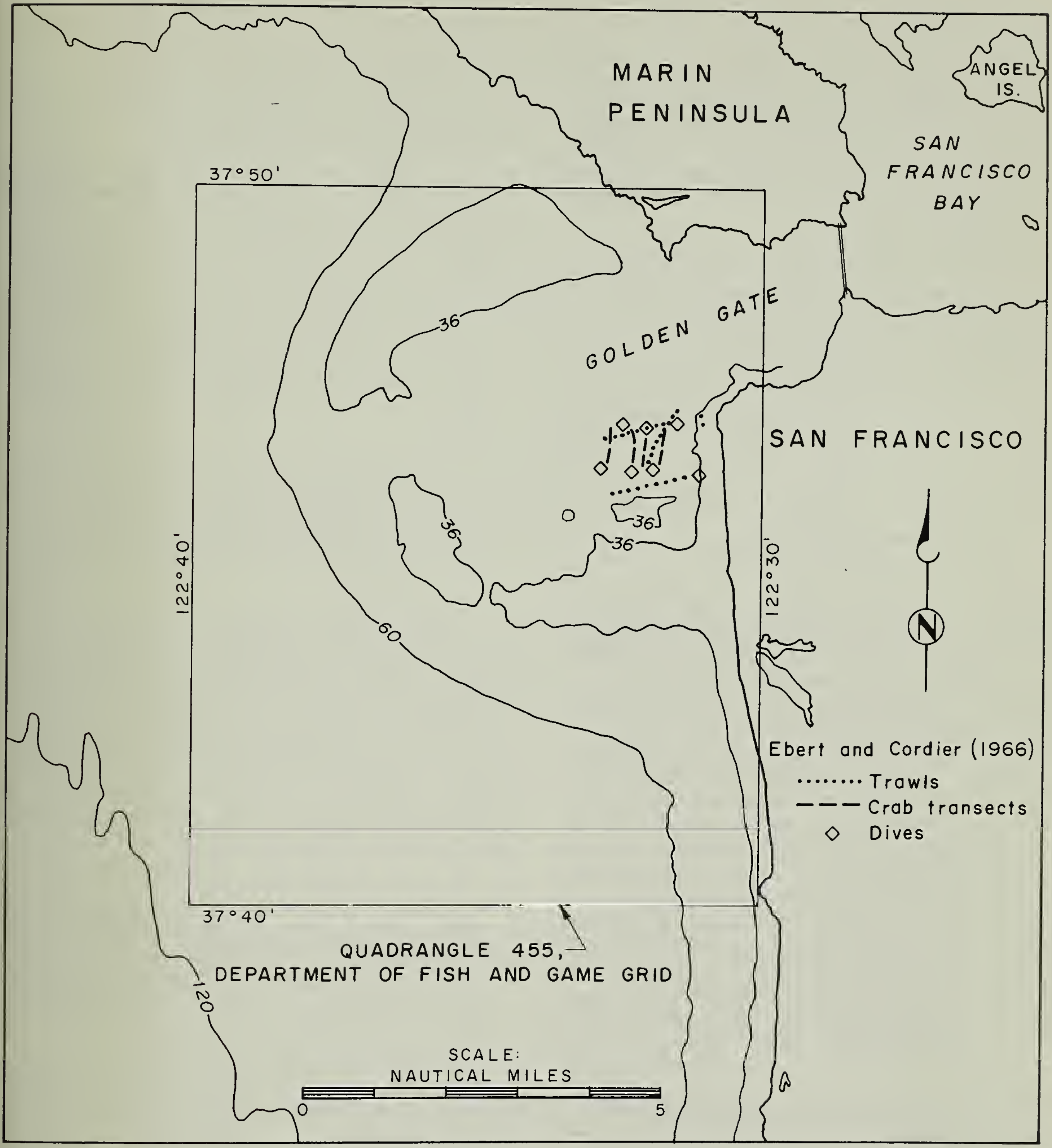


Fig. 5-7 **Location of Biological Study Areas in the Gulf of the Farallones**
Source: Reference 52 (Appendix A)

The California Department of Fish and Game further collates fin fish catch information by area of origin. Annual summaries are then presented in their Fish Bulletin series.[53] The particular area of interest to the San Francisco fin fishery is a quadrangle (Number 455) approximately ten miles by eight miles adjacent to the entrance of San Francisco Bay (Fig. 5-7). This square is part of a large grid which encompasses all coastal waters of California. There are almost a thousand squares for the entire state.

San Francisco area fisheries commonly refer to all catches landed in the bay area. The difficulty of designating exact catch location for all fish landed is obvious. In many cases fish landed in San Francisco are actually obtained from distant fishing grounds. Conversely, many catches obtained within the San Francisco area are processed outside of the area. A study of the San Francisco commercial landings[54] has shown that the majority of fin fish were caught within the Gulf of the Farallones. Sport fishing was concentrated along the coast from Point Reyes to Pillar Point and within San Francisco Bay.

The most important fin fishery in the San Francisco Bay area is that of the migratory salmon. Two principal species, the king and silver salmon, compose the vast majority of fish taken. The Northern Gulf of the Farallones and Northern San Francisco Bay contain the main routes of salmon on their upstream migration to spawning grounds at the San Joaquin and Sacramento headwaters. Most salmon delivered to the San Francisco area fish processing plants, however, are caught in the Gulf of the Farallones before the upstream migration has begun.

Another economically important fin fish which utilizes similar migratory routes as the salmon is the striped bass. Although this fish is not caught commercially, it supports a large and valuable sport fishery. The striped bass follows the bay routes of the salmon quite closely during periods of migration, but it is not found as extensively in the Gulf of the Farallones. In addition, striped bass are distributed more widely throughout Central San Francisco Bay during nonmigratory periods.

Fin fish investigations of the nearshore Gulf of the Farallones are very limited. One important study was made by Ebert and Cordier[52] during 1966 offshore of Seal Rocks within DFG quadrangle No. 455 (Fig. 5-7). Four trawling stations (a total of 7500 yards) yielded 22 fish species and a total of 162 pounds of fish and invertebrates. This small catch only prompted the authors to conclude that the Seal Rock area contained a "sparse or modest biotic community." The most abundant fish species recovered were the northern anchovy (*Engraulis mordax*) and the shiner perch (*Cymatogaster aggregata*). Few commercially important species were caught during the study. The only significant catches were those of the English sole, northern anchovy and sand sole.

The pelagic group fishery in the San Francisco area is largely composed of catches from three fish species; albacore, herring and anchovy. Of these albacore is the most important catch in size and dollar value.[53] The value of the pelagic group fishery in the San Francisco area has been declining over the past ten years mainly as a result of large drops in the catch of herring and anchovy. During the past few years this group's commercial value has played a small supporting role to the important stable group fishery of the San Francisco area.

The catch records from 1953 through 1968 of the principal fish species in the stable group fishery of the San Francisco area are listed in Table 5-2. Twenty-three species are listed by the Department of Fish and Game as belonging to the stable group fishery, but the 15 presented constitute more than 90 percent of the total catch. Of these, the salmon fishery is many times as valuable as the total remaining fisheries. The high value of the salmon fishery is caused partially by the high price that salmon command relative to the other fish species. The salmon catch in the San Francisco area was worth $1,279,000 in 1966, which can be equaled only by the market (Dungeness) crab fishery. Together these two fisheries compose more than 75 percent of the commercial fishing effort in the San Francisco area.

In terms of poundage, four fish species predominate the stable group fishery. The salmon and rockfish catches were the largest between 1953 and 1968, followed by English and Dover sole. Recent year catches have indicated that rockfish catches are becoming a smaller contributor to the total stable group fishery.

The stable group fishery has not exhibited as drastic a decrease in catch poundage as the pelagic group. Small yearly fluctuations are present, but any low annual catch of one fish species is often offset by an increase in one of the many other species. There does appear, however, to be a downward trend in the total fish catch in the late sixties. Even these low catches, however, appear to be within the normal range of previous fluctuations.

Table 5-2 Principal Fisheries of San Francisco Bay

Species	Catch per year - lbs x 10^6																16 year total lbs x 10^6	1966 dollar value x 10^3
	1953	1954	1955	1956	1957	1958	1959	1960	1961	1962	1963	1964	1965	1966	1967	1968		
Salmon	3.3	3.4	3.9	2.9	1.3	1.7	4.6	2.9	2.7	2.1	3.5	3.5	3.6	2.2	1.8	2.2	46.6	1,279
Rockfish	4.2	3.0	1.6	2.9	2.8	4.2	4.9	3.3	2.2	2.0	2.4	1.8	1.6	1.6	0.9	0.6	40.2	105
English sole	a	a	2.3	1.7	1.6	1.5	1.0	0.7	1.3	2.2	1.9	2.0	2.0	1.9	1.9	1.7	23.7[a]	171
Dover sole	a	a	0.5	1.1	0.5	1.0	0.8	1.5	1.4	1.5	2.0	2.7	2.6	2.5	1.3	0.3	19.7[a]	144
Petrale sole	a	a	1.6	0.9	0.7	0.7	0.8	0.6	0.8	0.9	0.9	1.0	0.9	1.1	0.8	0.5	12.2[a]	157
Sablefish	0.2	0.4	0.4	0.8	0.4	0.5	0.7	0.8	0.7	0.9	0.8	0.8	0.7	1.0	0.5	0.1	10.7	42
Rex sole	a	a	0.5	0.5	0.4	0.4	0.5	0.5	0.4	0.5	0.5	0.5	0.5	0.4	0.3	0.2	6.1[a]	31
Sanddab	0.3	0.4	0.3	0.4	0.4	0.5	0.3	0.2	0.2	0.2	0.3	0.4	0.2	0.3	0.2	0.3	5.1	23
Lingcod	0.2	0.2	0.3	0.3	0.3	0.5	0.4	0.4	0.4	0.3	0.3	0.3	0.2	0.3	0.2	0.2	4.8	24
Flounder	0.2	0.2	0.4	0.2	0.3	0.3	0.2	0.1	0.1	0.1	0.3	-	0.2	0.2	0.4	0.2	3.4	15
Ocean shrimp	-	0.1	0.3	0.3	0.5	0.2	-	0.1	-	0.2	0.2	-	0.2	-	-	0.2	2.3	15
Shark	0.1	0.1	0.1	-	0.1	0.1	0.1	0.1	0.1	0.2	0.2	0.1	0.1	0.1	0.1	0.1	1.7	5
Skate	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	1.6	1
Turbot	-	0.1	0.1	0.1	0.1	-	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	1.4	3
Calif. halibut	-	-	-	-	-	-	0.1	-	0.1	-	0.1	0.2	0.2	0.2	0.3	0.2	1.2	59
Yearly total	12	13	12	12	9.4	12	15	11	11	11	13	13	13	12	8.9	7.0	180.7	

[a] Sole catches not broken down to species until 1955, therefore totals only represent thirteen years. Sole cates for 1953 and 1954 totalled 3.2 and 4.8 million pounds, respectively.

Source: Catch data from Department of Fish and Game Fish Bulletins, dollar values from Odemar et al (1968).

Annual California and San Francisco area commercial fish catches for the period from 1953 to 1968 are plotted in Fig. 5-8. Total commercial fish catch for the San Francisco area has declined sharply since 1965. In order to understand the makeup of these fishery fluctuations, certain components of the total commercial fishery were subtracted from each graph. The sardine fishery, which previously was a major component of the statewide commercial fish catch, has essentially collapsed since 1958. This fishery has been subtracted from the statewide totals to present total fluctuations in existing fisheries. From the San Francisco area commercial fishery the crab and pelagic fish catches have been subtracted in subsequent plots to illustrate the importance of the stable group fishery.

It is evident that downward trends exist in total commercial fish catches for both the state and the San Francisco area. The decline in the total fish catch from the San Francisco area, however, is relatively more pronounced. Since 1965 the decline appears to be mainly a function of a decrease in the stable group fishery. From 1958 to 1963 the decline appeared to be mainly related to declines in the pelagic group and crab fisheries. When the pelagic group and crab fisheries are subtracted from the total fish catch, the result is a record of the stable group fishery which modestly fluctuated about 13 million pounds caught each year until the 1966-68 decline.

Sport fishery effort in the San Francisco area is primarily related to party boat and shore fishing for salmon, striped bass and rockfish (Table 5-3). There is also an increasing small boat effort particularly for salmon and striped bass. Detailed statistics for sport fisheries are not as complete as for commercial fin fisheries because of the extreme difficulty of data collection. Odemar et al[54] listed 113 species in the total sport fishery of the San Francisco area. Young[55] tabulated annual party boat catches for twelve species of fish from San Francisco Bay ports. The major components of the party boat landings were (in descending order) salmon, rockfish, striped bass, lingcod and California halibut. Over 50 percent of the total sport landings between 1953 and 1967 were salmon.

Intertidal Wildlife. Five major wildlife habitats exist in the San Francisco estuary: marshland, tidal flats, salt ponds, rocky intertidal areas and open water. The tidal flats can be further divided by sediment type into mud flats and sandy beaches. Each of these habitats supports a distinct community of organisms and plants. Each also plays an important role in the total marine ecology of the San Francisco area.

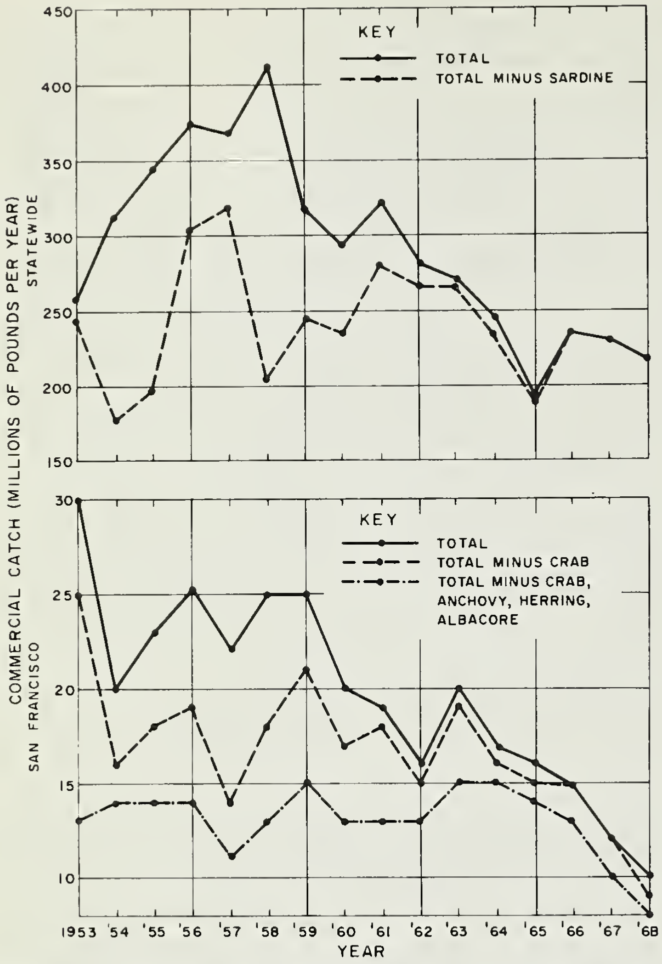


Fig. 5-8 **Annual California and San Francisco Area Commercial Fish Catches**
Source: Reference 54 (Appendix A)

A scheme of relative wildlife habitat value was developed by the San Francisco Bay Conservation and Development Commission.[56] The extent of each habitat in the area adjacent to San Francisco is shown in Fig. 5-10. The figure shows that the majority of intertidal land surrounding the City of San Francisco has a relatively fair value as a wildlife habitat. Much of the ocean and Central Bay intertidal areas consist of sandy beaches which typically support a low diversity of animals. Chief inhabitants of these intertidal areas are sand burrowers (sand crabs, amphipods, clams, etc.) and shore birds. Along the eastern and northeastern intertidal areas of the city, land fill and pier construction have drastically limited the availability of marine habitats for wildlife. In these areas attached organisms on pilings and rocky breakwaters constitute the major biota.

The highest relative value of wildlife habitats is found along the rocky coasts of Marin County, in the shallow areas of Richardson Bay and along the Berkeley waterfront. All of these areas are distant from any projected outfalls from the City of San Francisco. Areas under investigation in this study for possible outfall construction fall entirely within the lowest classification of relative values for wildlife habitats as outlined by the San Francisco Bay Conservation and Development Commission.

Biological Resource Summary. Odemar, et al[54] published the most extensive survey of biological-related resources from the marine environment surrounding the San Francisco area. They divided the marine environment into major study areas and summarized the available data on fisheries, diving, intertidal effort, marine laboratories, public parks and available shoreline for each area (Fig. 5-11). The study area adjacent to the City of San Francisco is Area II and includes the entire Gulf of the Farallones from Point Reyes to Pillar Point. The summary of beneficial uses of the marine environment is outlined in Table 5-3. The resources of adjacent study areas are also presented for comparison with Area II. Area I includes the marine environment from Point Reyes north to Ft. Ross. Area III is located south of Area II and extends to the northern edge of Monterey Bay. A brief discussion of Odemar's findings is included in this summary.

The commercial fishery for salmon is of primary importance in the Gulf of the Farallones. Trawl effort is also substantial for rockfish, soles and other flatfish. The major salmon fishery is located nearshore and within the main migratory routes (Fig. 5-9). Trawl fishing is primarily located offshore and distant from the City of San Francisco.

The largest sport fishery in central coastal California is located in the waters surrounding San Francisco (Area II). Salmon, rockfish, striped bass and lingcod are the main components of the sport fishery. Party boat catches are the main components of the salmon and striped bass fisheries. A large shore fishery is also present within the study area.

Study Area II contains extensive tidepools, especially at Duxbury Reef in Marin County and from Rockaway Beach to Pillar Point in San Mateo County. The study area also supports a moderate amount of clam digging and a limited amount of skin diving.

Marine laboratories are located at Bolinas and at several locations within San Francisco Bay. Three biological reserves are located within Study

Table 5-3 Summary of Beneficial Uses of Marine Environment in the San Francisco Area

Beneficial uses	Sub area[a]					
	I		II		III	
	Fort Ross to Point Reyes	Percent	Point Reyes to Pillar Point	Percent	Pillar Point to Sand Hill Bluff	Percent
Commercial fisheries						
Average annual landings in pounds for selected species, 1957 to 1966[b]						
Salmon	1,060,786	36.5	1,662,356	57.2	183,631	6.3
Market crab	646,173	22.7	2,058,256	72.3	143,604	5.0
Ocean shrimp	147,192	100.0	-	-	-	-
Oyster(cultivated)	127,164	100.0	-	-	-	-
Origin of average annual catch, lbs, and effort, hours, for all trawl caught species, 1962 to 1966[c]						
Dover sole	664,159	30.4	140,504	6.4	1,379,117	63.2
English sole	680,095	37.3	840,319	46.1	304,207	16.6
Petrale sole	238,235	28.9	300,683	36.5	284,115	34.6
All other flatfish	298,047	21.9	741,416	54.4	322,271	23.7
Rockfish	451,210	21.0	606,387	28.3	1,086,469	50.7
Sablefish	323,708	35.5	136,401	15.0	451,279	49.5
Lingcod	90,316	43.7	101,177	48.9	15,234	7.4
All other trawl caught species	53,791	19.2	169,453	60.5	57,065	20.3
Total trawl-catch for all species	2,799,561	28.8	3,036,340	31.2	3,899,757	40.0
Trawl effort all species	5,139	31.0	7,148	43.1	4,295	25.9
Average annual commercial landings, all species, 1957 to 1966[b]						
Pounds:			19,724,320			
Value:			$3,202,444			
Sport fisheries						
Average annual ocean party boat, landings in numbers of fish, for all species, 1962 to 1966[b]	25,100	10.6	114,441	48.5	96,294	40.9
Origin of average annual ocean partyboat catch in numbers of fish for selected species 1962 to 1966[c]						
Salmon	1,048	1.6	63,464	98.1	185	0.3
Rockfish	21,914	13.7	65,736	41.1	72,405	45.2
Striped bass	2	-	4,119	99.7	12	0.3
Lingcod	677	7.1	3,525	37.2	5,279	55.7
Origin of average annual party boat effort in angler days for all species, 1962 to 1966[c]	3,237	4.7	56,433	81.7	9,426	13.6
Ocean skiff catch and effort						
Catch, numbers of fish:	23,669[d]	-	not available	-	not available	-
Effort, angler days:	12,877[d]	-		-	11,050[e]	-

Continued on next page

Table 5-3 Summary of Beneficial Uses of Marine Environment in the San Francisco Area (Continued)

Beneficial uses	Sub area[a]					
	I		II		III	
	Fort Ross to Point Reyes	Percent	Point Reyes to Pillar Point	Percent	Pillar Point to Sand Hill Bluff	Percent
Ocean shore effort in angler days	43,485[d]	18.7	111,359[f]	47.9	77,494[e]	33.4
Ocean pier effort in angler days[e]	-	-	-	-	-	100.0
Free diving and scuba diving effort[g]	xx	-	x	-	xx	-
Clam digging effort[g]	xxx	-	xx	-	x	-
Tide pooling effort[g]	xxx	-	xxx	-	xxx	-
Non-fishery usage						
Number of marine laboratories	2	40.0	2	40.0	1	20.0
Number of proposed and existing marine reserves	4	50.0	3	37.5	1	12.5
Number of public parks and public access areas	6	20.7	12	41.3	11	38.0
Miles of ocean shoreline contained in public park and access areas	94.0	75.4	19.2	15.4	11.3	9.2
Ocean shoreline park use counts[h]	1,370,645	34.3	655,050	16.4	1,965,136	49.3

[a] Reference figure 5-11.

[b] Port of landing data.

[c] Origin block data.

[d] 1957-61 data (Miller and Gotshall, 1965).

[e] 1966 data Golden Gate to Point Lobos (Miller and Odemar, 1968).

[f] 1957-61 and 1966 data combined.

[g] x least use
xx moderate use
xxx greatest use

[h] Data only for parks reporting attendance figures.

Source: "A Survey of the Marine Environment From Fort Ross, Sonoma County to Point Lobos, Monterey County." Department of Fish and Game, State of California, MRO No. 68-12 July, 1968.

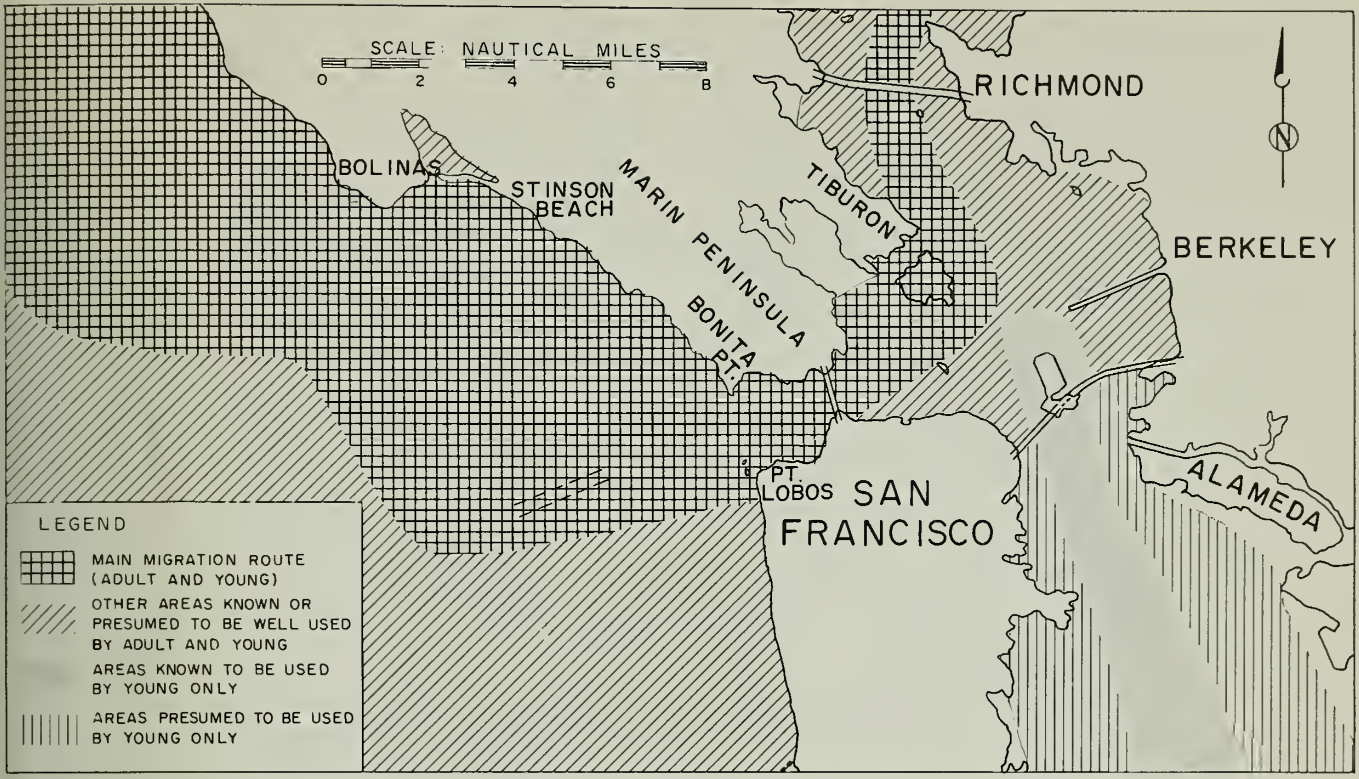

SCALE: NAUTICAL MILES
0
2
4
6
8
BOLINAS
STINSON BEACH
MARIN PENINSULA
BONITA PT.
TIBURON
RICHMOND
BERKELEY
N
PT. LOBOS
SAN FRANCISCO
ALAMEDA
LEGEND
MAIN MIGRATION ROUTE (ADULT AND YOUNG)
OTHER AREAS KNOWN OR PRESUMED TO BE WELL USED BY ADULT AND YOUNG
AREAS KNOWN TO BE USED BY YOUNG ONLY
AREAS PRESUMED TO BE USED BY YOUNG ONLY

Fig. 5-9 Main Migration Routes of Salmon in San Francisco Bay and the Gulf of the
Source: Reference 56 (Appendix A)

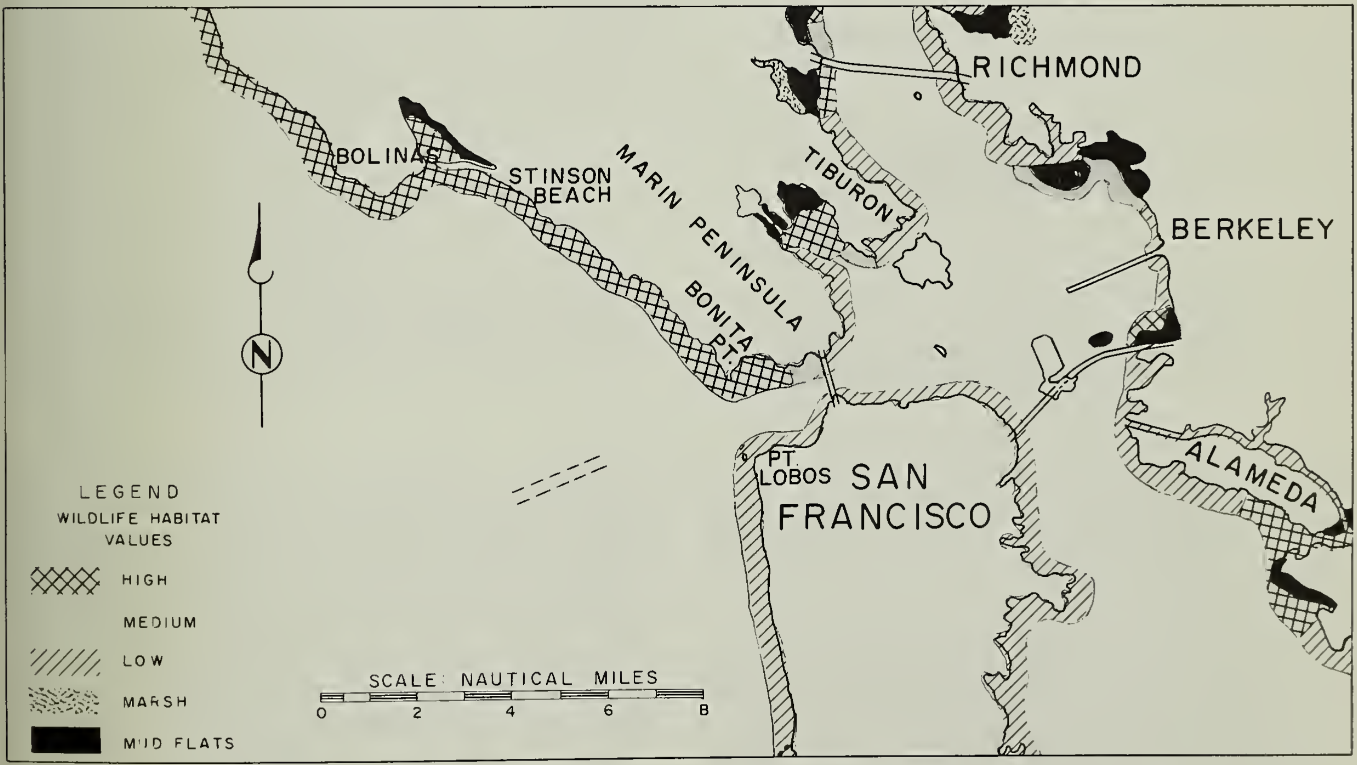


Fig. 5-10 Wildlife Habitats in San Francisco Bay and the Gulf of the Farallones
Source: Reference 56 (Appendix A)

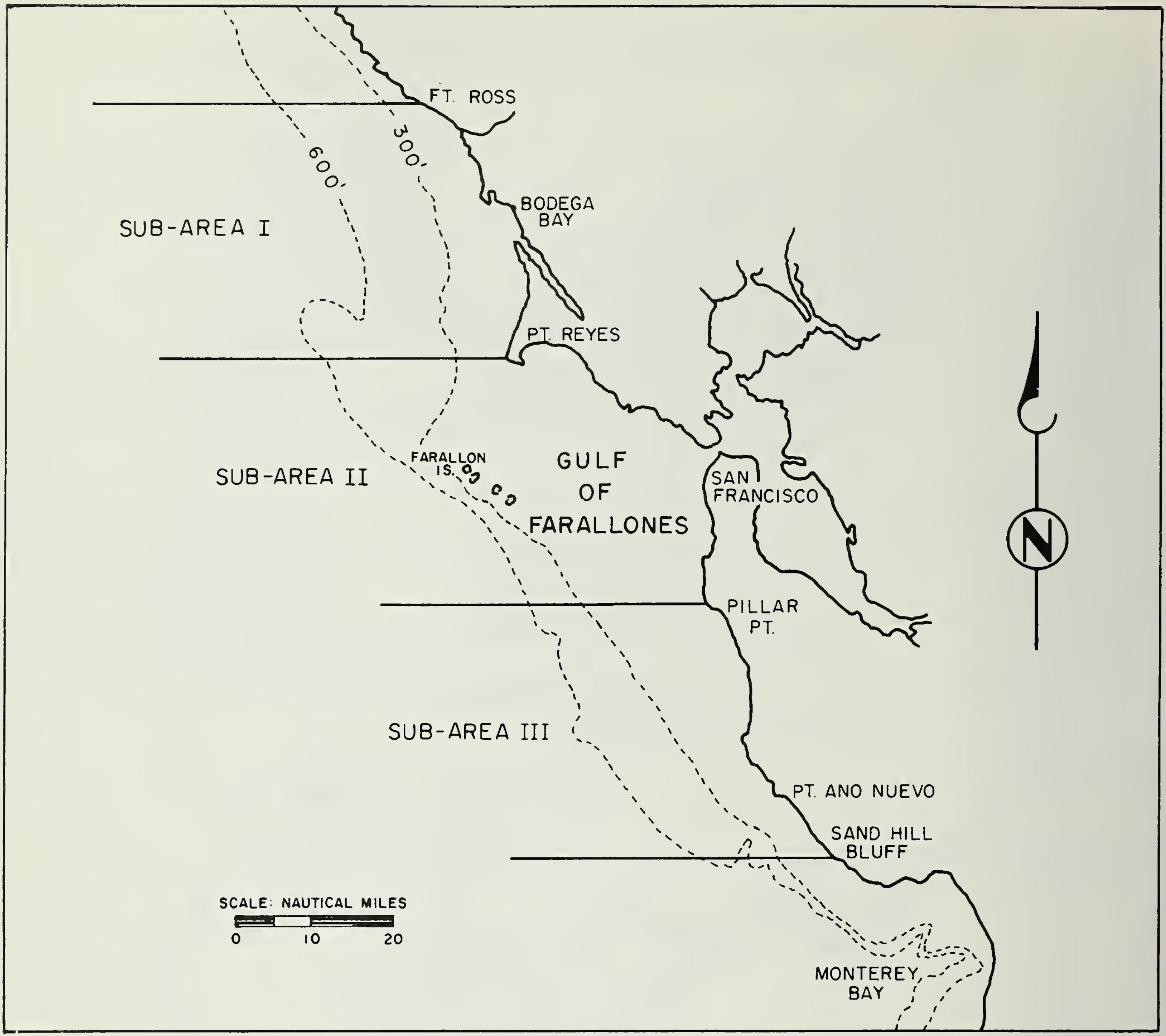


Fig. 5-11 California Department of Fish and Game Study Areas in the Vicinity of San Francisco. Source: Reference 54 (Appendix A)

Area II at Duxbury Reef, Farallon Islands and at Moss Beach. The area also has twelve public parks and public access areas.

Dungeness Crab

The Dungeness crab, *Cancer magister*, also known as the market crab, is one of the most important commercial fisheries on the Pacific coast of North America. Annually this fishery produces over 25 million pounds of crab with a value to fishermen in excess of five million dollars. Along the northern coast of California only the salmon fishery compares in size of catch and market value to the Dungeness crab fishery. From 1915 through 1968 the ocean and bays of the San Francisco area have yielded an average of over two million pounds of market crab per year. The economic importance of the Dungeness crab fishery to the San Francisco area emphasized the need for a thorough understanding of the ecology of this species, particularly where its natural history could be influenced by man's activities.

In order to insure that the commercially important crab fishery of the San Francisco area would not be detrimentally affected by any proposed waste discharge into the marine environment, a major portion of the ecological program was focused on studies relating to the Dungeness crab. The investigation was divided into three major sections. The first section included a review of the literature associated with the life history and commercial fishery of the Dungeness crab in the San Francisco area; the second section involved field investigations to determine the abundance and distribution of all life stages of Dungeness crab in the marine environment surrounding San Francisco; and the third section studied its response in the laboratory to dilutions of San Francisco municipal effluent. The results of the literature reviews are presented in this section of the study, while the field and laboratory investigations are presented in later sections of this chapter. Information obtained from literature reviews of the life history and commercial fishery of Dungeness crab was an important contribution to the development of both the field and laboratory programs.

Life History. Adult Dungeness crab have been recorded from almost all areas of San Francisco Bay and the Gulf of the Farallones. The crab is apparently tolerant of some fresh water and was recorded in 1921 as being universally distributed from Carquinez Strait to Point San Mateo.[57] It has been postulated that control of fresh water runoff from the Sacramento Delta has maintained low salinities in the upper San Francisco estuary and consequently reduced this distribution until presently adult Dungeness carb are common only in central portions of San Francisco Bay. Environmental stress due to man's activities may also have contributed to the more restricted distribution of the market crab within the San Francisco estuary.

Dungeness crab typically exhibits a preference for sandy bottoms. The species is occasionally found on silt or mud substrates of bays, where it is commonly discolored, but rarely does it reside on rocky shores. The Dungeness crab is an indiscriminate scavenger of the sandy bottom. An examination of adult crab stomachs has revealed an assemblage of food organisms such as oysters, shrimps, worms, mollusks and fish. Cannibalism of young or injured individuals has also been observed. In addition, saprophytic metabolism (feeding on the remains of dead organisms) is quite common among crabs.[59]

Mating occurs in the San Francisco area during the months of February through June. Copulation typically takes place in deep offshore waters. Sperm is stored by the female for several months during which time the eggs mature. Studies in British Columbia have indicated that female crabs migrate inshore in order to breed, but tagging studies by the California Department of Fish and Game have indicated that California market crab are generally non-migratory.[59] [53] Once the eggs have sufficiently matured, they are simultaneously transferred to the abdomen and fertilized. Fertilization typically takes place from October through December. The fertilized eggs are carried on specialized appendages on the female's abdomen until they hatch. Hatching generally occurs in January and February. One female crab may carry as many as one million eggs.

Eggs of Dungeness crab may hatch as prezoea or as first stage zoea. Mackay[59] described the hatching of Dungeness crab as always starting with the pre-zoea (protozoea), but in a more recent study Poole[60] indicated that the pre-zoea larvae only emerged from prematurely ruptured eggs. The pre-zoea stage is relatively inactive and swims only by contortions of the body. Mackay reported that the pre-zoea larval stage was always of short duration and subsequently hatched into first stage zoea.

Life history studies of the Dungeness crab have been severely limited by the difficulty of identifying zoea taken in plankton samples and the inability to rear crab larvae in the laboratory. The presently accepted normal development of a *C. magister* larva is depicted in Fig. 5-12, by Mir[61] and Poole.[60] There are five zoeal stages and one megalops in the complete larval development of *Cancer magister*. All zoeal stages, megalops and young adult are found within the plankton community, although large megalops and young crab frequently become too heavy to remain in the water column and settle to the bottom.

The first stage zoea is approximately 2.5 mm long and metamorphoses around 18 days after hatching into a second stage zoea. Each successive larval stage is somewhat larger than the previous stage due to growth during development. Larval crab are largely predacious, and copepods supply the bulk of their food. Second stage growth usually extends to the 29th day after hatching, when the third stage zoea emerges. The third, fourth and fifth stages lasted 13.6, 14.6 and 22.4 days respectively in laboratory studies conducted by Poole.[10] The total time required to develop from the egg to the first adult form was 111 days.

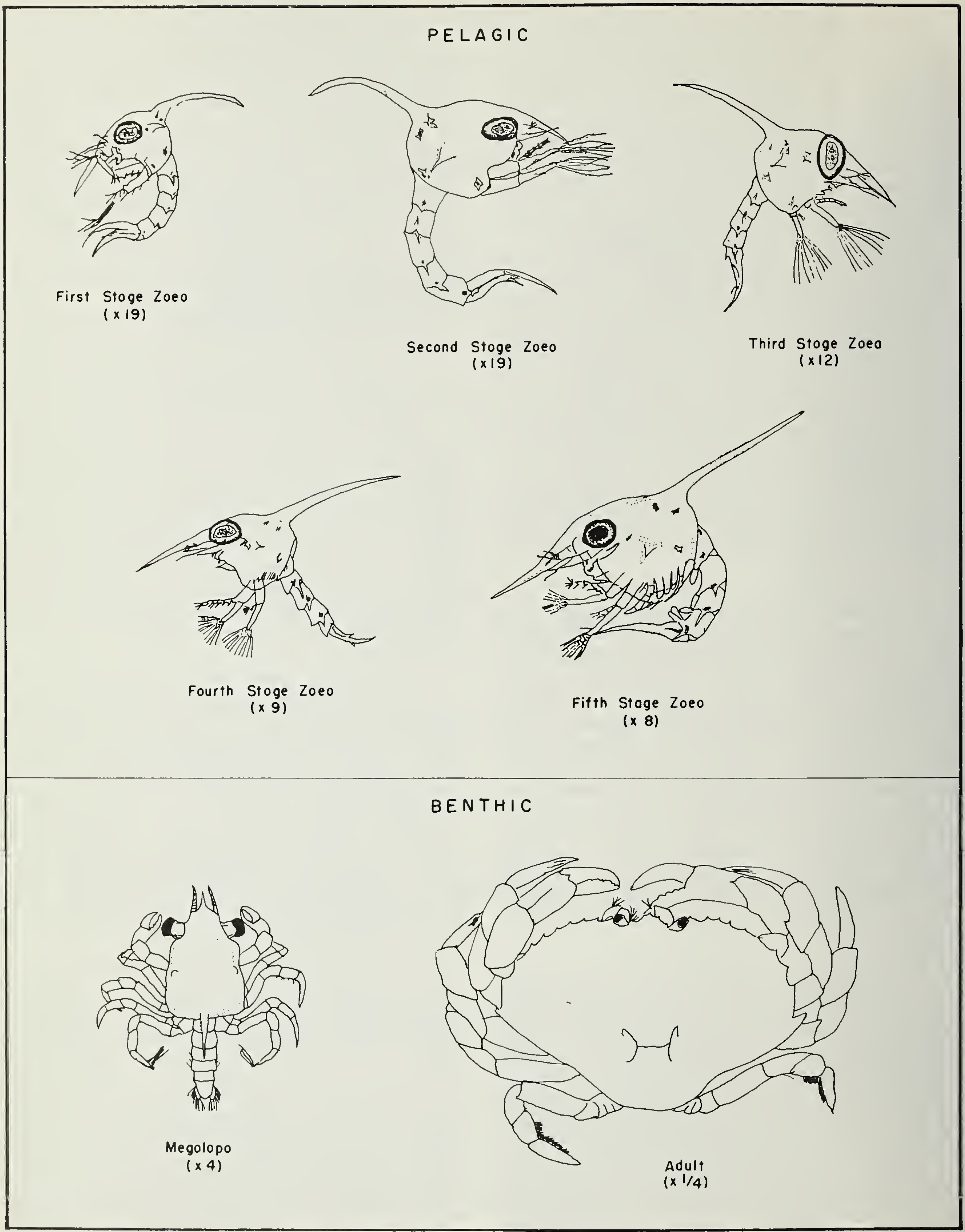


Fig. 5-12 Life Stages of the Dungeness Crab

Poole observed that a number of factors could influence development time. The most important effects on larval development were created by changes in the water temperature. Increases in water temperature greatly reduced the time at each zoeal stage. The majority of Pool'e studies were conducted at 51 deg C , which is comparable to water temperatures surrounding San Francisco. Poole also noted that there were some differences in structure and size between laboratory-reared larvae and those collected in the ocean. In general, ocean-reared larvae were considerably larger than laboratory-reared individuals. Finally, Reed[78] noted that fluctuations in salinity between 20 and 30 ppt may influence development and that salinities less than 15 ppt were lethal to Dungeness crab zoea.

Once the young crab obtains adult form, growth is accomplished by molting of the hard outer shell about once a year. The female generally molts prior to copulation and the male after copulation. Sexual maturity is attained in both the male and female after about two years, at which time the male is larger than the female.[62] In the San Francisco area the majority of male crabs reach commercial size in four to five years.

The importance of understanding the life history of the Dungeness crab was emphasized in observations made by Poole[60] during his laboratory investigations. Poole noted that the first stage zoea was the most difficult life stage of *C. magister* to maintain in the laboratory. This stage frequently had mortalities as high as 70 percent. Therefore, to properly assess the response of *C. magister* to possible exposure of municipal effluent it was essential that the most sensitive life stage, the first stage zoea, be studied. Information such as this, which related to larval sensitivity and methods of culturing, provided an important basis for the laboratory investigation of the Dungeness crab.

Dungeness Crab Fishery. Nine species of crabs of the genus *Cancer* occur on the Pacific coast of America. Four of these species are taken commercially in California, but *C. magister* the Dungeness crab, constitutes at least 99 percent of the entire commercial catch.

The range of the Dungeness crab extends from the Bering Sea to Magdalena Bay, Baja California, but relatively few specimens are collected south of Point Conception, California. In the San Francisco area the principal fishing grounds extend from Point Reyes in the north ot Miramontes Point in the south (Fig. 5-13). Although the majority of fishing effort is presently concentrated between 20 and 40 fathoms, the most productive fishing grounds in the past were restricted to nearshore waters (less than 10 fathoms) and San Francisco Bay.[54] Two main hypotheses have been proposed to explain the present lack of commercial size crab within the nearshore waters. The first explanation proposes that over-fishing in shallow waters has reduced the number of crabs below levels necessary to maintain or increase the nearshore populations. The second explanation suggests that changes in the San Francisco Bay outflow have made conditions unfavorable for crab populations. Neither of these explanations is entirely satisfactory, however, as large numbers of juvenile crabs are frequently sampled at nearshore locations. These juveniles could form the basis of an adult population. Further, it would be expected that juvenile crabs would be more sensitive to environmental stress caused by changes in the quality of the San Francisco Bay outflow and hence would be the first to disappear.

Fluctuations in crab populations at San Francisco, Eureka and in Washington are presented in Fig. 5-14. The crab catches per year at each locality are a reasonable measure of the existing adult populations, since the fishery is regulated so that smaller crabs are allowed to escape capture and be available for future year catches. Large fluctuations in crab catches at each locality are common. The populations of market crabs along the west coast appear to be cyclic, with highs and lows coinciding at widely diverse locations. The decreases in crab populations are thought to be the result of changes in oceanographic conditions, but no documentation of responsible factors has been achieved. Whatever the exact cause of fluctuations in the Dungeness crab population, it apparently is influential over the entire marine environment from Alaska to southern California.

From Fig. 5-14 it is apparent that the San Francisco crab fishery has experienced a considerable decline since the 1956-7 season when over 8.9 million pounds of Dungeness crab were caught. Both the Monterey and Morro Bay crab fisheries have had similar declines. Fluctuations in the San Francisco crab fishery were similar to statewide fluctuations until 1964, when the northern fisheries began to recover from the 1958-62 decline. The decline in crab catch at San Francisco, however, has persisted for a much longer time. Through 1968 the San Francisco crab catch was still at a fraction of the previous fishery.

The Dungeness crab localities that have not recovered from the 1958-62 population decline

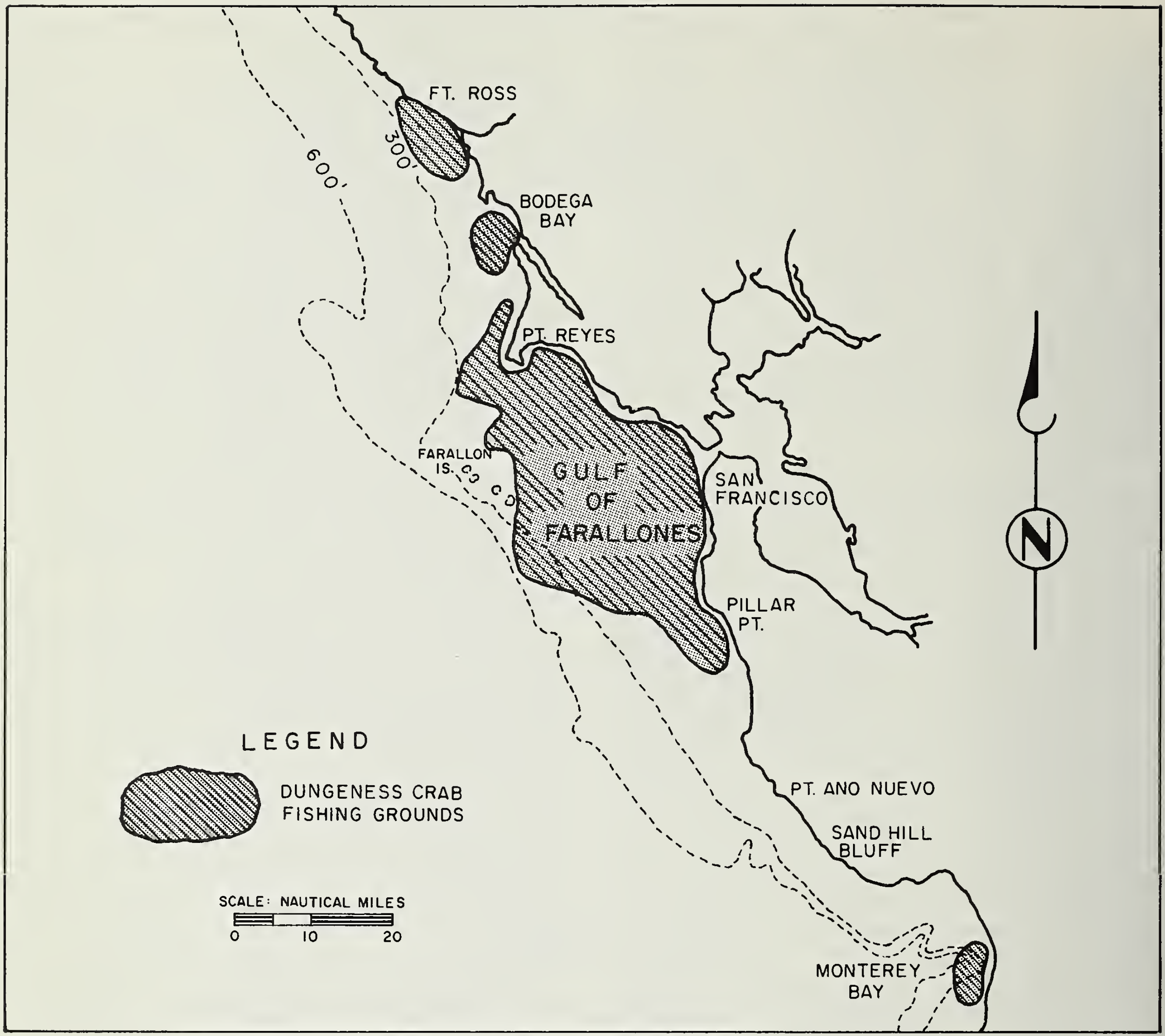


Fig. 5-13 Dungeness Crab Fishing Grounds in the San Francisco Area

(San Francisco, Monterey and Morro Bay) are at the southern limit of the crab fishery. These areas also correspond to the southern limit of the main distribution of the population, which implies that normal environmental conditions in these areas would be only marginally favorable for sustaining Dungeness crab populations. If unusual oceanographic conditions were responsible for a reduction in the Dungeness population in the southern fishing grounds, the environment may not have been sufficiently favorable for population recovery. Further, as the principal current system during the time that Dungeness larvae are in the plankton is from the south, the Gulf of the Farallones is partially dependent upon larvae from areas further south for repopulation; and as those areas are also depopulated and in marginally favorable areas for crab, this would cause a lag in the recovery of the local fishery.

Population fluctuations in the shrimp catch for the San Francisco area have also shown a major decline in recent years (Fig. 5-15). The pattern of decline and recovery of shrimp harvest is very similar to the crab catch fluctuations. The Eureka shrimp fishery declined during the 1962-5 period and recovered during the 1966-68

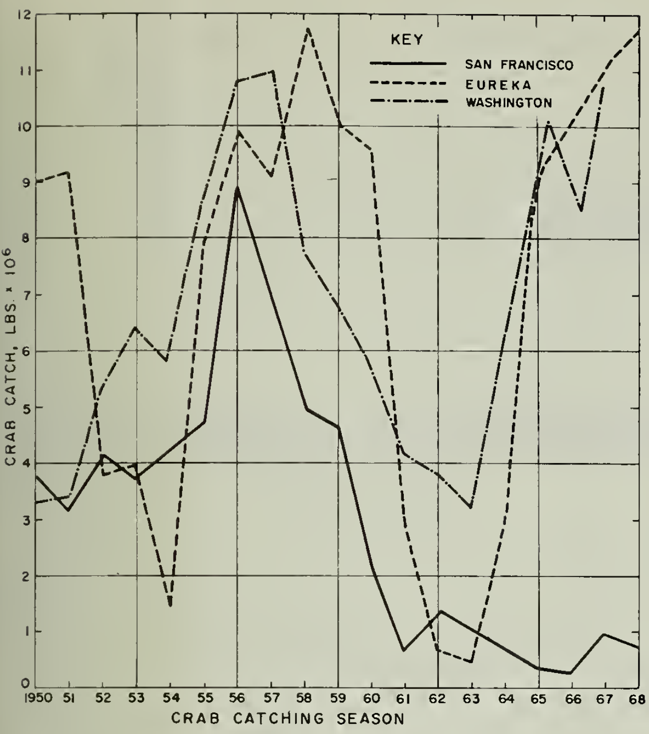


Fig. 5-14 Fluctuations in Dungeness Crab Populations for Northern California and Washington.
Source: Reference 53 (Appendix A)

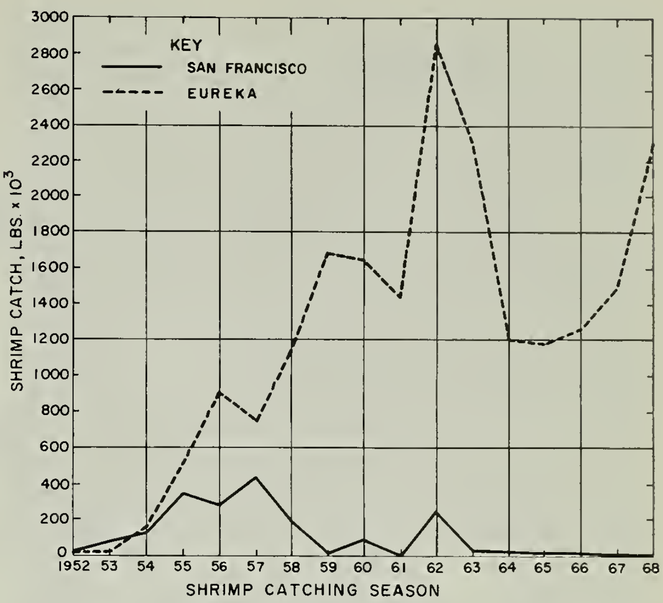


Fig. 5-15 Shrimp Catches for San Francisco and Eureka Areas.
Source: Reference 53 (Appendix A)

period. San Francisco had a similar decline, but the fishery has not recovered. It was originally proposed that the same factors that influenced the crab catch fluctuations might be responsible for shrimp fluctuations, but a more detailed investigation has shown that the periods of decline and recovery at Eureka did not occur at the same time as the crab fluctuations.

The highest shrimp catch (1962), in fact, corresponded to a very low crab catch. It was also found that the continued decline in the San Francisco area could be explained by a lack of demand for the fishery and a correspondingly reduced commercial effort.

The possible effects of silting and industrial waste in the Gulf of the Farallones have been investigated as contributing factors in the sustained low crab catches. No correlation was found, however, between these factors and fluctuations in the crab population.

Pesticides have also been considered a prime factor in analyzing the underlying causes for the crab decline. Recent studies[63] have demonstrated that high pesticide accumulations in crustaceans can affect molting survival and larval development. Fig. 5-16 summarizes the levels of pesticides (DDT, DDE and DDD) found in eggs and larvae of *C. magister* at various localities in northern California.[54] The Gulf of the Farallones and Drakes Bay had the highest levels of pesticides recorded of the localities studied. Average levels of accumulated pesticides exceeded 180 ppb in the Gulf of the Farallones, and the level in immature crabs from Drakes Bay exceeded 105 ppb. These two localities compose the major fishing grounds for the San Francisco Dungeness crab industry. In addition, only these two localities had measurable amounts of DDT accumulations in larval crabs. Unfortunately, it is not know what constitutes an acute or chronic lethal level of pesticide residues in the eggs of larvae of *Cancer magister*, and so the relatively high levels of pesticides in the Gulf of the Farallones and Drakes Bay must be considered circumstantial evidence. Certainly, additional studies should be undertaken to investigate the possible effects of pesticide residues on long term survival in Dungeness crab.

The review of information concerning the Dungeness crab fishery in the San Francisco area introduced a new objective into the ecological program: it is not only important that existing crab populations be protected from detrimental waste discharges but it is also important that the marine environment be given every chance to increase crab populations to those densities that

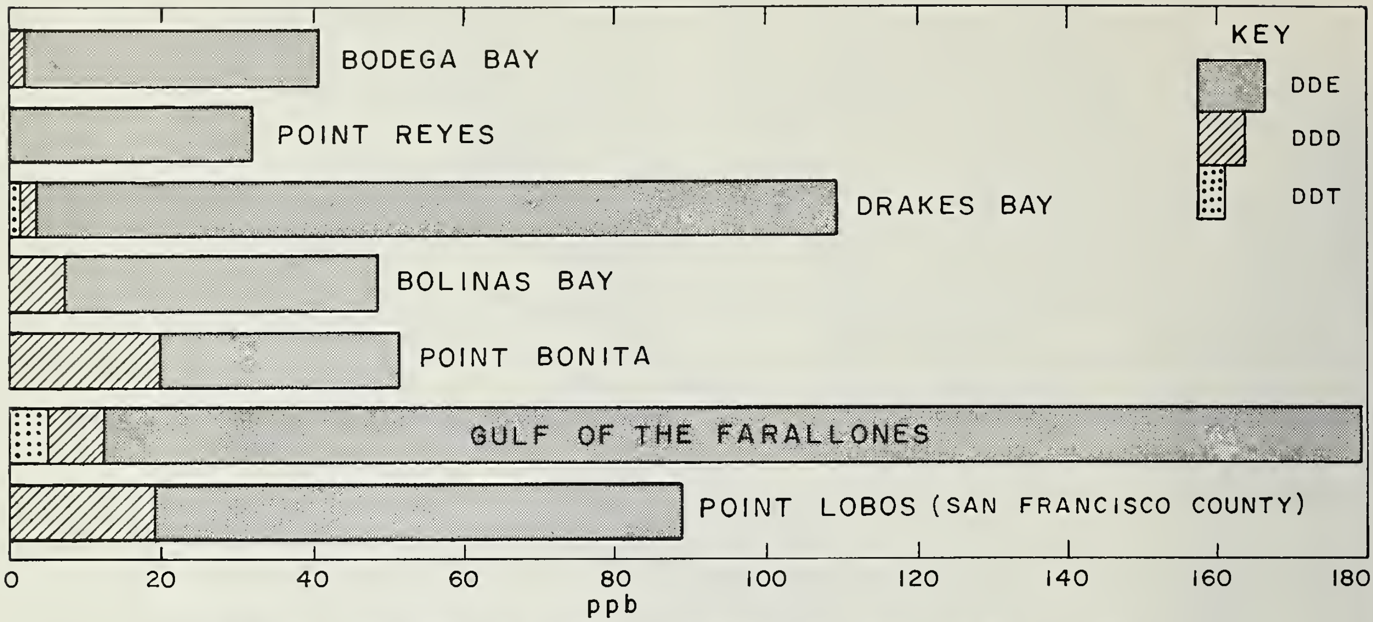


Fig. 5-16 Pesticides Residues in Dungeness Crab from Northern California
Source: Reference 54 (Appendix A)

were once found in the marine environment surrounding San Francisco. There is, however, no evidence to indicate that the recent decline in the crab fishery in the Gulf of the Farallones is attributable to municipal waste discharges.

FIELD INVESTIGATIONS

Biological field investigations were conducted in San Francisco Bay and the Gulf of the Farallones from December 1969 through December 1970. The purpose of these investigations was to gather information about existing conditions in the marine and estuarine environments around the City of San Francisco. This information formed the basis for an estimate of the effect of a municipal waste discharge on the aquatic environments studied. The field investigations complemented and lent direction to concurrent laboratory studies on the response of marine organisms to municipal sewage effluent and provided a base line from which future changes in the environment can be documented and assessed. Field programs were scheduled on a seasonal basis in order to measure the normal annual fluctuations in the environment.

The field investigations were divided into five phases: (1) plankton studies; (2) benthic studies; (3) diving studies; (4) intertidal studies; and (5) in-situ cage experiments. Each of these studies was designed to analyze an important segment of the environment or measure the effect of an existing discharge. The results of each study provided information about a biological community which would likely be influenced by marine waste discharges.

Plankton Studies

Plankton is composed of microscopic plant and animals which lack the ability to swim against ocean currents. Plankton plays a primary role in the food chain for marine organisms and provides a nursery for many larval forms of commercially important species. The nature of their habitat means that plankters are subject to any conditions in which water movement places them. This combination of importance to future commercial species, vital link in food chain, and inability to move from an undesirable area emphassizes the necessity of protecting the plankton from detrimental environmental changes.

Plankton surveys were conducted in the Gulf of the Farallones from December 1969 through October 1970. A cooperative program of plankton sampling and sample identification was arranged in the fall of 1969 between the California Department of Fish and Game and Brown and Caldwell. During the program the Department of Fish and Game conducted four offshore plankton cruises and Brown and Caldwell conducted five nearshore plankton cruises. Standard sampling and identification procedures were established, and information derived from the joint venture plankton surveys was shared by both organizations.

Plankton samples were obtained by both Brown and Caldwell and the Department of Fish and Game in order to measure the abundance of *Cancer magister* zoea in the Gulf of the Farallones. This information would enable a prediction of the larval crab populations that would be influenced by a waste discharge. If toxic effects were identified in the laboratory this information would be extremely important. The plankton samples were also analyzed for diversities and population sizes. These analyses were used to interpret the role of the plankters in the food chain and the productivity of the waters in different areas.

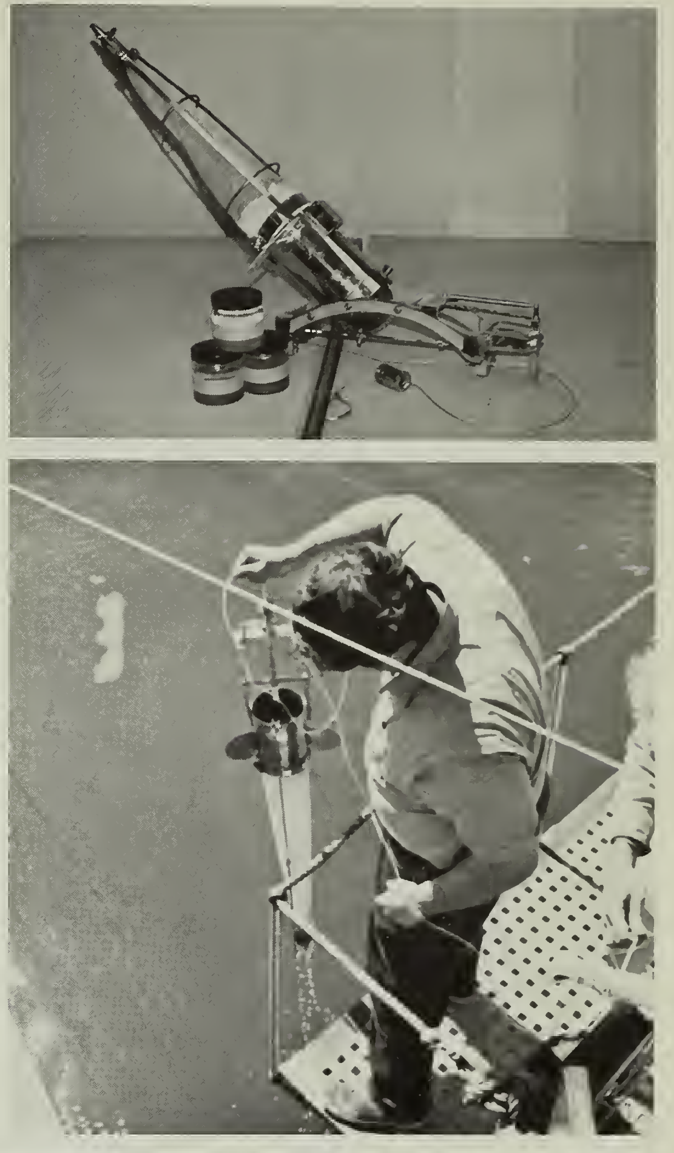
Plankton Cruises and Stations. The stations that were sampled during the plankton survey program are identified in Fig. 5-17. The California Department of Fish and Game conducted cruises in December, 1969, and in February, April and May, 1970. During these cruises 14 stations were regularly sampled. Brown and Caldwell conducted cruises in February, April, May, June and October, 1970. During these cruises 19 stations were sampled.

Ten of the Department of Fish and Game stations were determined to be out of significant influence from San Francisco Bay and were collectively analyzed as "ocean stations". The remaining stations were considered influenced to varying degrees by San Francisco Bay water and were collectively analyzed as "bar stations".

Methods and Materials. Plankton was collected from two depths at each of the sample stations. The initial program called for collections at two and ten meters, but the ten meter plankton tow was not appropriate at some bar stations because of shallow water. At these stations the deep tow was raised to eight meters.

All collections were obtained using a number two mesh net attached to a Clarke-Bumpus plankton sampler. This net size allowed most of the phytoplankton to pass through but retained most of the larger zooplankters. The Clarke-Bumpus sampler is equipped with a metering wheel which revolves in response to water passing through the sampler. The metering wheel was calibrated by towing the sampler without a net at various speeds over a measured course. Two tows were made in opposite directions at each speed.

Plankton tows in the Gulf of the Farallones were made by towing the sampler beside the boat at a speed of two to four knots for five to fifteen minutes. The sampled plankton was washed from the collection bucket into glass jars and preserved in the field with formaldehyde.



Plankton samples were collected using a Clarke-Bumpus volumetric sampler.

All plankton samples were returned to the laboratory for analysis. Each sample was thoroughly mixed before an aliquot was removed for identification. The samples were subdivided into aliquots by using the wye splitting method to prevent organisms from sticking to the glass surfaces. The size of the aliquot was determined by visual observation of the density of the plankton in the collection jar, and varied from 50 milliliters to the entire sample.

Plankton samples were analyzed in the laboratory using a dissecting microscope.

The samples were placed in small Petri dishes with measured grids inscribed in the bottom for counting and identification. Plankton identifications were made in accordance with the keys from Davis,[64] Wickstead,[65] and Newell and Newell.[66] Large zooplankton were identified and counted under a dissecting microscope. Detailed analyses of crab zoea and identification of small zooplankters were performed using a standard microscope. The body structure of many crab zoea is very similar to *Cancer magister* zoea, and detailed dissection was required for accurate identification. *C. magister* zoea were identified using the references of Lebour, Mir, Poole and Thrash.[67 61 60 69]

Plankton Results. The attempt to document the distribution and population of Dungeness crab zoea in the Gulf of the Farallones produced unexpected results. From the 85 plankton samples analyzed only three *C. magister* zoea were reported. Two of these were found to be in one plankton tow, Brown and Caldwell Station C, eight meters, on February 24, 1970. The other Dungeness zoea was reported from an eight meter nearshore plankton tow taken in April. Because of the late date, the validity of this identification is questionable. By April most Dungeness zoea have reached adult stage and settled to the bottom.

Although few Dungeness zoea were found, many other invertebrate larvae were reported from the plankton tows, and zoea of other *Cancer* species (*C. productus* and *C. antennarius*) were abundant. A complete identification of the plankton samples is presented in Volume 2, Data Supplement.

The results of the plankton survey indicated that either Dungeness zoea did not exist in the Gulf of the Farallones at the time of sampling or that they were not sampled during the cruises. The fact that adult gravid females and juvenile Dungeness crabs were found by the California Department of Fish and Game in trapping studies suggested that the sampling program was at fault. Several possible reasons can be postulated for the lack of Dungeness zoea in the samples: (1) zoea were present in the Gulf of the Farallones at a very low density and the sampling results simply reflect this density; (2) the larval population was not evenly distributed and the sampling program resulted in stations at the nonfavorable locations, or tows at the wrong depth or time of day; (3) insufficient volumes of water were sampled for a representative measurement; or (4) the sampling program missed the period during which most zoea were in the plankton. The importance of the Dungeness crab to the San Francisco fishery suggests that additional and more comprehensive investigations should be undertaken.

Even though very few Dungeness larvae were found, a complete analysis was performed on each plankton sample. This was done to document the abundance and types of zooplankters that are subject to influence by a municipal waste discharge into the Gulf of the Farallones. Some of the representative zooplankton that were identified during the study are presented in Fig. 5-18 and Fig. 5-19.

Table 5-4 lists the predominant zooplankters for each cruise month at the ocean and bar stations. The table is further divided into deep and shallow tows. In December, 1969, salps, which are pelagic tunicates, dominated the two-meter tows at both the ocean and bar stations. No predominant species were evident at the stations at ten meters depth. During the February cruises tunicates were again predominant at the ocean stations, but now they were abundant at both two and ten meters. During this time copepods had replaced salps at the bar stations as the dominant group. Copepods were abundant at both two and ten meters.

In April copepods were found to be abundant at all stations and at both shallow and deep tows. Also, at this time numerous fish eggs were found in the ocean samples. Non-*Cancer* crab zoea also composed a major fraction of the zooplankton at the ten meter ocean stations.

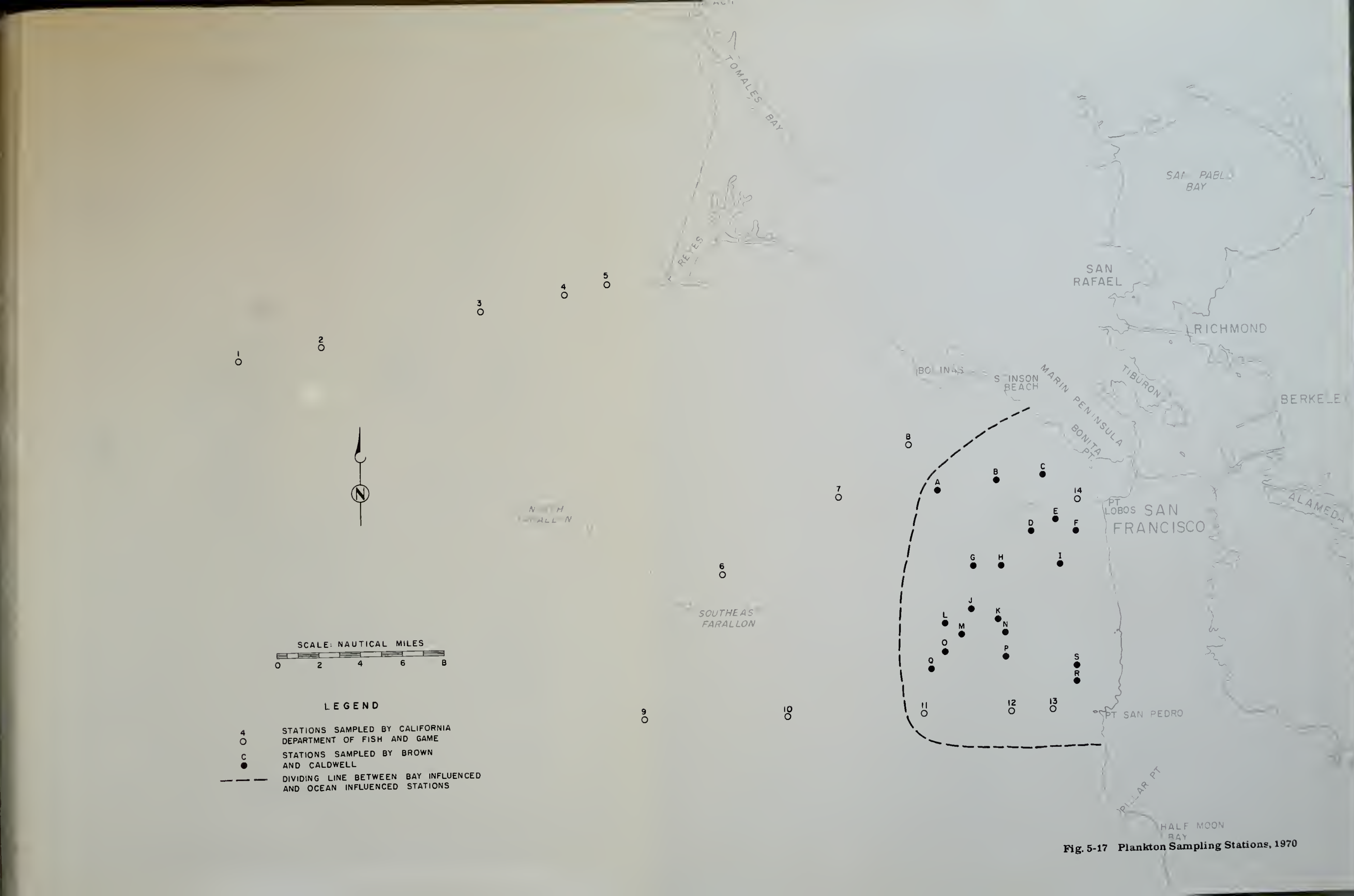


Fig. 5-17 Plankton Sampling Stations, 1970

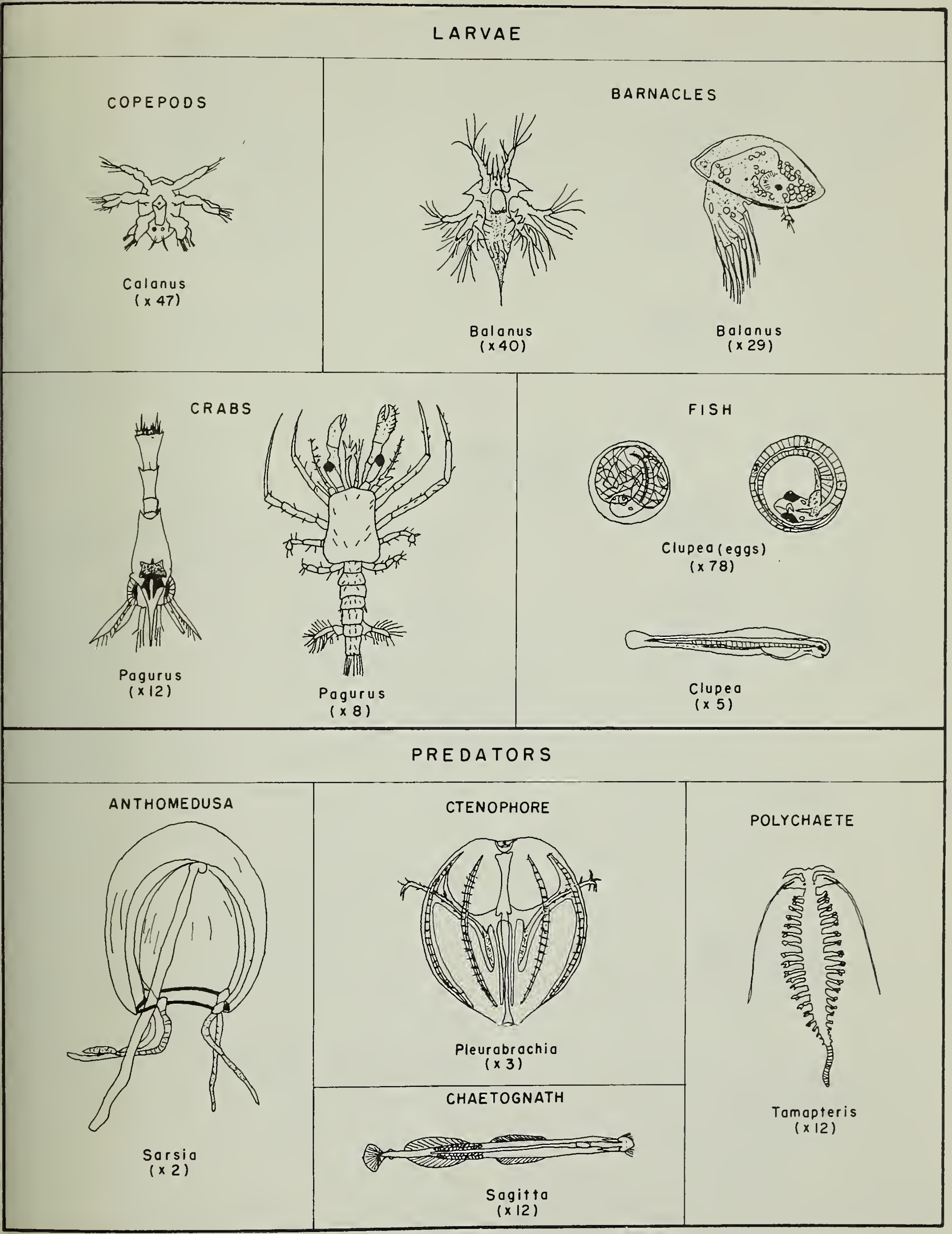


Fig. 5-18 Typical Zooplankton Larvae and Predators in the Gulf of the Farallones

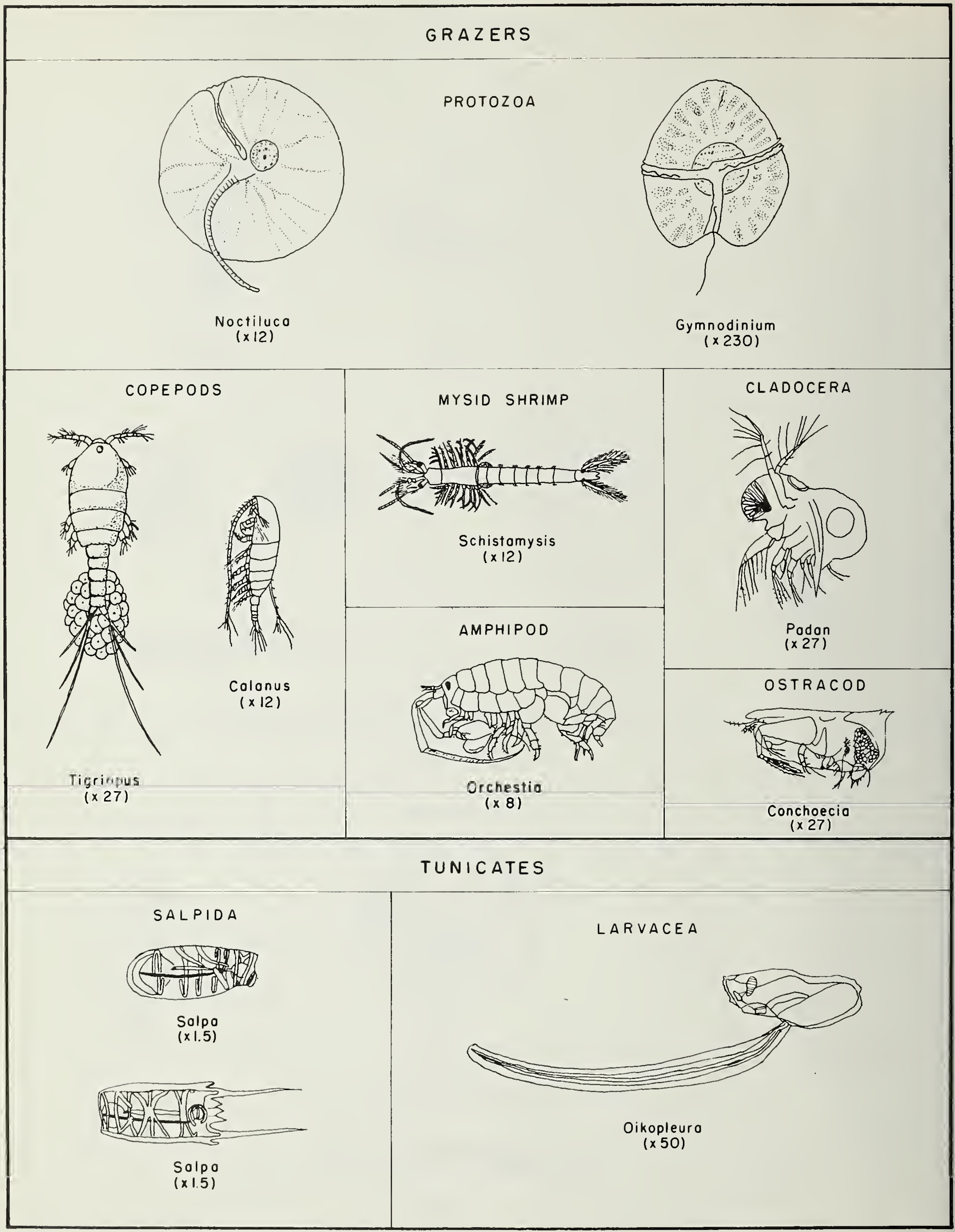


Fig. 5-19 Typical Grazing Zooplankton in the Gulf of the Farallones

Table 5-4 Predominant Seasonal Zooplankters

Date	Ocean		Bar	
	2 meters	10 meters	2 meters	10 meters
December 1969	Salps Copepods	No predominant types	Salps	No predominant types
February 1970	Larvaceans Salps	Larvaceans Salps	Copepods	Copepods
April 1970	Fish eggs Copepods	Copepods Fish eggs Crab zoea	Copepods	Copepods Barnacles
May 1970	Fish eggs Codepods	Fish eggs	Copepods Barnacles Fish eggs	Copepods Barnacles
June 1970	No samples	No samples	Noctiluca Copepods	Noctiluca
October 1970	No samples	No samples	Copepods Larvaceans	Copepods Larvaceans Polychaetes

During May fish eggs became even more abundant in the plankton samples and showed up as a predominant group in all but the deep bar stations. The analyses indicated that April and May were the months in which most marine fish laid eggs. Copepods continued to be a major fraction of the plankton samples during May, and barnacles became abundant in the nearshore (bar) stations at all depths. As the California Department of Fish and Game conducted no plankton cruises during June or October, 1970, the ocean stations were not sampled. During the nearshore cruise in June *Noctiluca* became the predominant genus in the plankton samples. *Noctiluca* is a holozoic marine flagellate.

If zooplankton analyses for all stations are divided into trophic levels (grazers, predators and juveniles) some interesting results are obtained (Fig. 5-20). During late spring and early summer the number of grazing zooplankton decreased while the number of predators and juveniles increased. This relationship between grazers and predators has been documented by Buchsbaum[20] and results from predators feeding on the grazers. On the other hand, the large increase in juveniles is believed to have resulted from reproduction of the grazers either when they were found in abundance or as a reaction to the predator effect on their population. Most of the juveniles were grazer nauplii or fish eggs. A marked increase occurred in the grazer population during June and was found to correspond to phytoplankton blooms during that time.

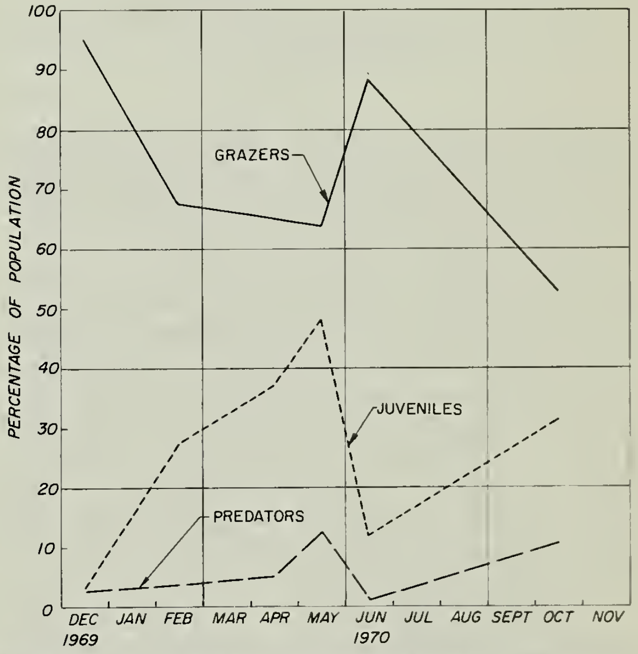


Fig. 5-20 Zooplankton Trophic Levels in the Gulf of the Farallones

The average density of zooplankton during the sampling period is graphed in Fig. 5-21. The general shape of the curves demonstrates a customary decline in zooplankton number through the winter and early spring with a large scale increase occurring in late spring and early summer. The high December, 1969 populations at both the bar and ocean stations were found to be mainly composed of salps. The very large May increase in

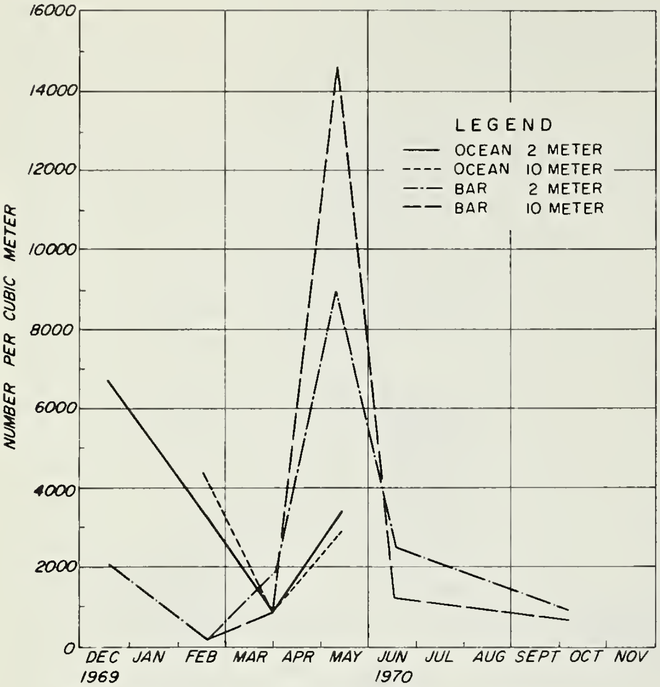


Fig. 5-21 **Zooplankton Density in the Gulf of the Farallones**

numbers resulted almost entirely from large increases in the copepod population. The increase in copepods corresponded to increased phytoplankton populations.

There was no consistent difference in zooplankton numbers between the ocean and bar stations or between depths. However, during bloom conditions the bar stations did have significantly greater numbers than the ocean stations. Typically, nearshore waters support greater populations of plankton than the open ocean because of higher nutrient levels. As the ocean stations were not sampled during the later field investigations, population comparisons could not be made with the bar stations.

Fig. 5-22 presents graphs of average diversity indices for ocean and bar stations during the sampling program. A slightly modified diversity index as suggested by Margelef[71] from Gleason[72] was used in analyzing the relationship between numbers of organisms and number of species in the plankton samples. This index (∂) was computed from the following formula:

$$\partial = \frac{S-1}{\ln N}$$

Where S is the number of species identified in the plankton sample and N is the total number of organisms counted. This index is relatively simple to compute and has found wide usage in the field of marine ecology. In this analysis no particular emphasis was placed on the choice of index, as it was used only as a tool to relate the composition of the numerous plankton samples both spatially and temporally.

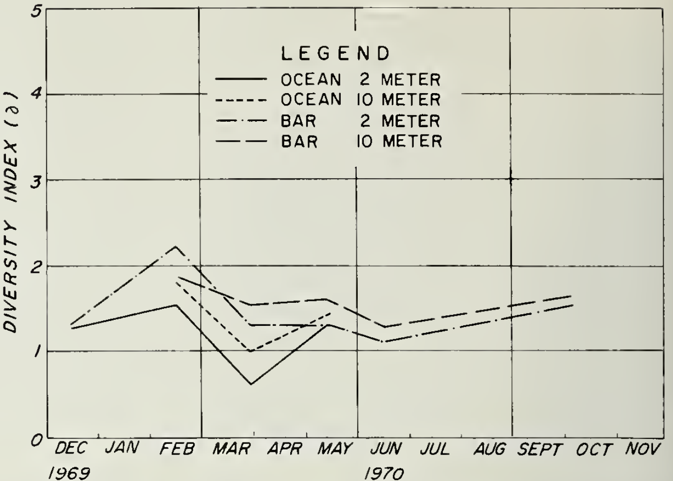


Fig. 5-22 **Zooplankton Diversity in the Gulf of the Farallones**

The results of diversity index analysis indictated that there were no large differences between stations during most of the sampling period. There was, however, a consistent tendency for the diversity index to be higher at the bar stations than at the ocean stations. During the February sampling the average diversity index of the bar stations was found to be highest of all sampling dates. During this time the predominant zooplankters were copepods.

No diversity indices were calculated for the ocean stations after May, as they were not sampled. Although there was a slight tendency towards higher diversity indices with depth, the correlation was not significant.

Composite data from Figs. 5-21 and 5-22 are presented in Fig. 5-23. In this graph the average number of organisms per cubic meter and the average diversity indices for all stations are plotted. Although both curves fluctuated during the study program, there are no definite patterns. The most obvious observation is that the diversity of organisms was inversely correlated with the density of organisms during the sampling program. The diversity index was generally highest when the total number of organisms was lowest. The highest number and low diversity were measured in May, while the highest diversity and a low number were recorded in February.

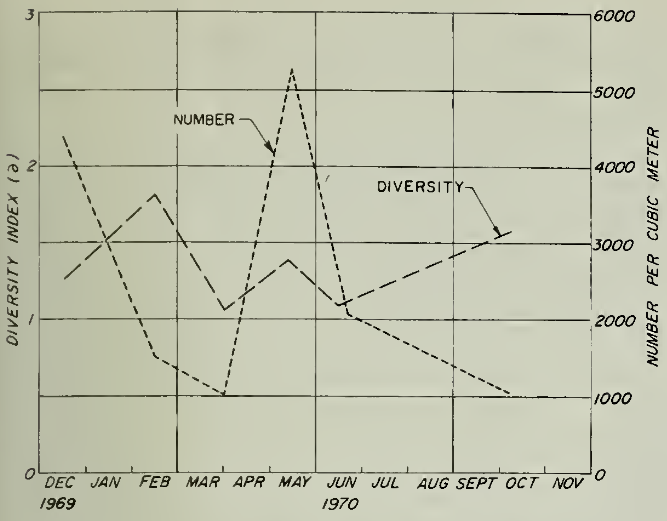


Fig. 5-23 Average Zooplankton Density and Diversity - All Stations

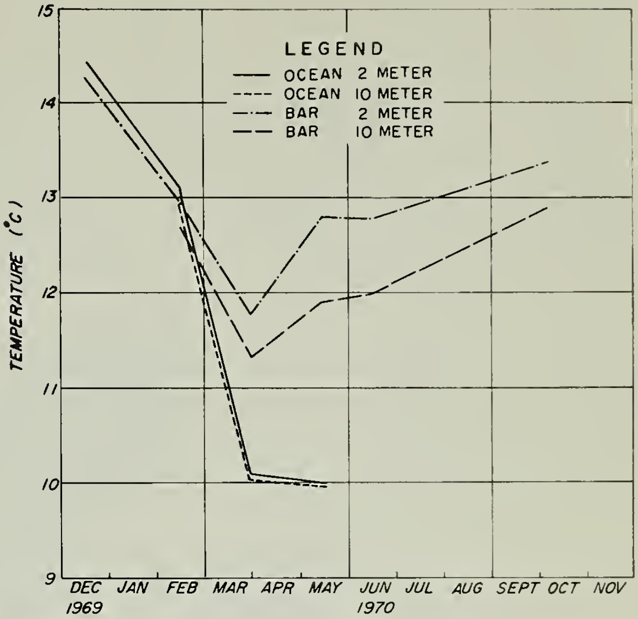


Fig. 5-24 Water Temperature at Zooplankton Stations

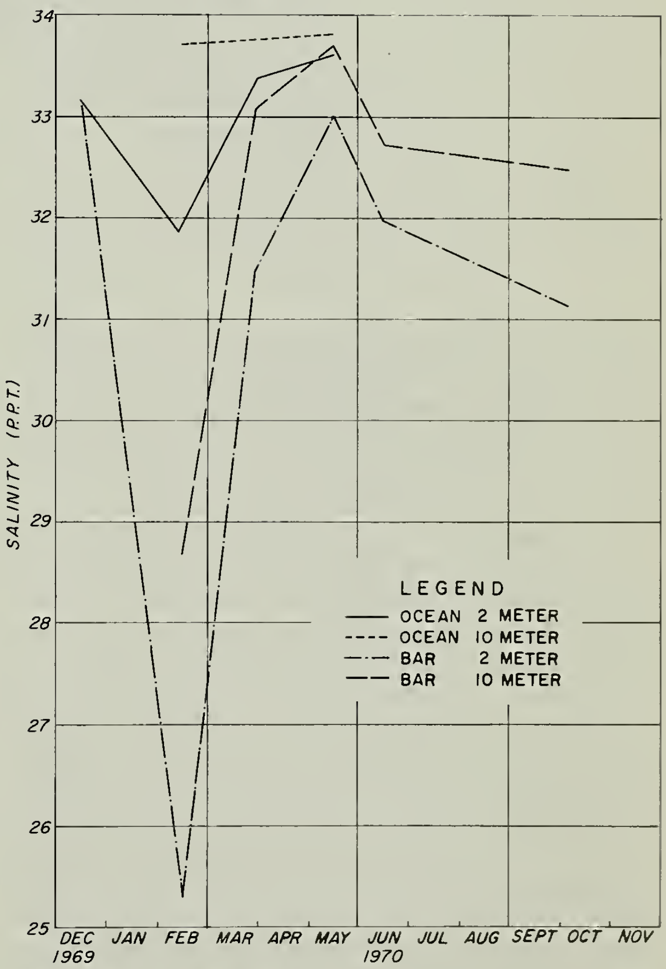


Fig. 5-25 Water Salinity at Zooplankton Stations

The inverse relationship between diversity and density is a typical phenomenon for aquatic populations. Conditions become more favorable for one species and it outgrows its competitors, which become extinct in that area. The mechanism is most clearly demonstrated in stressed environments, where only a few organisms survive but do extremely well.

The average temperatures, salinities and water densities measured during the plankton collections are presented in Figs. 5-24, 5-25 and 5-26, respectively. Each parameter was represented for the two depths sampled at the ocean and bar stations. These physical characteristics were chosen for study because they were believed to be the most influential to plankton populations.

Fig. 5-24 shows that water temperatures were the highest at both bar and ocean stations in December 1969 and decreased regularly through late spring, 1970. This late spring decrease corresponded to the period of ocean upwelling. The effect of upwelling on water temperatures was most apparent at the ocean stations. Later, in the summer and fall, temperatures again began to rise. During the warm water period tunicates were the most abundant zooplankters while copepods, fish eggs and *Noctiluca* became dominant in colder water. These observations agreed with those of Moore[73] and Wimpenny.[74]

The salinity graph (Fig. 5-25) illustrates that there was a major reduction in salt concentration at the bar and two-meter ocean stations in early 1970. This reduction corresponded to the period of high fresh water runoff from the San Francisco

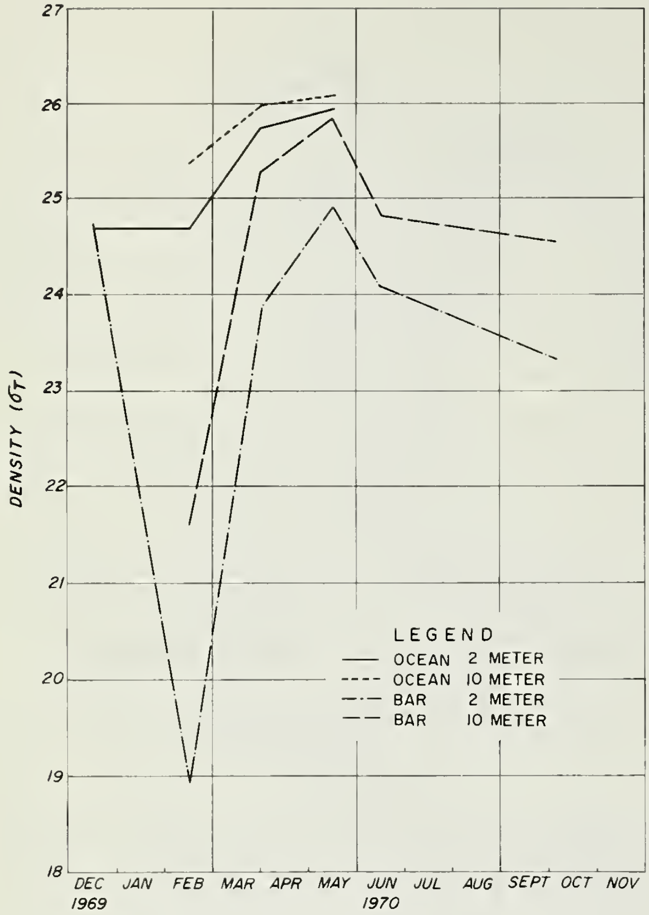


Fig. 5-26 Water Density at Zooplankton Stations

Bay-Delta. The salinities returned to normal ocean concentrations throughout the summer and were again reduced at the plankton stations in the fall. In February 1970 copepods first became dominant at the bar stations. Copepod population growth appeared to be correlated to reduced salinity.

The density of water (as expressed by σ_T) at the various stations (Fig. 5-26) was calculated from the temperature and salinity data. The shape of the curves illustrates the fact that the densities were most affected by salinity changes. In waters of low density, characterized by low salinity, many species of zooplankton have difficulty staying afloat. This ofter results in a reduction of plankton populations during periods of low density. The greatest number of organisms was measured at the ocean stations during December, 1969 when the water was more saline and consequently more dense. The increase in numbers at the bar stations during May, 1970 corresponded to the ocean upwelling period. The predominant plankters found during the low water density periods of this study were copepods and *Noctiluca* both of which are highly mobile zooplankters. During high density periods less mobile plankters such as tunicates were dominant.

The data were analyzed statistically to see if there was any correlation between plankton measurements and salinty, temperature or density of the sample waters. If correlations existed, predicitions could be made about plankton populations from measurement of these physical parameters. The data analyses are summarized in Table 5-5. Generally speaking, correlations greater than 0.4 are significant. Plankton diversity showed a slight correlation with temperature only at the two-meter ocean stations. At the eight-meter bar stations there was an indication that diversity was correlated with salinity and density. However, all correlations of plankton diversity with oceanic conditions were somewhat tenuous.

The overall average values for all measurements are indicated in Table 5-6 for both depth and location. Factor analysis of the average values demonstrated that only the relationships between tamperature and depth and temperature and location were consistently correlated. The correlations were 90 and 95 percent, respectively.

Plankton Summary. The plankton survey program resulted in very few Dungeness crab zoea being captured. Only three *Cancer magister* zoea were identified in the 95 samples analyzed. The plankton sampling program, rather than the lack of zoea in the Gulf of the Farallones, was probably responsible for the negative results, since the number of zoea captured seems to be totally out of

Table 5-5 Correlation Between Plankton Diversity and Oceanic Conditions

Area	Depth of tow	Correlation coefficients between diversity and physical parameters[a]		
		Temperature	Salinity	Density
Ocean	2 meters	+0.41	-0.36	-0.34
	8 meters	+0.04	0	0
Bar	2 meters	-0.18	-0.11	-0.30
	8 meters	+0.35	+0.50	+0.80

[a] The correlation coefficient indicates the closeness of relationship between two variables. A coefficient of 1.00 indicates perfect positive correlation; a coefficient of 0 indicates no correlation; and a coefficient of -1.00 indicates perfect negative correlation.

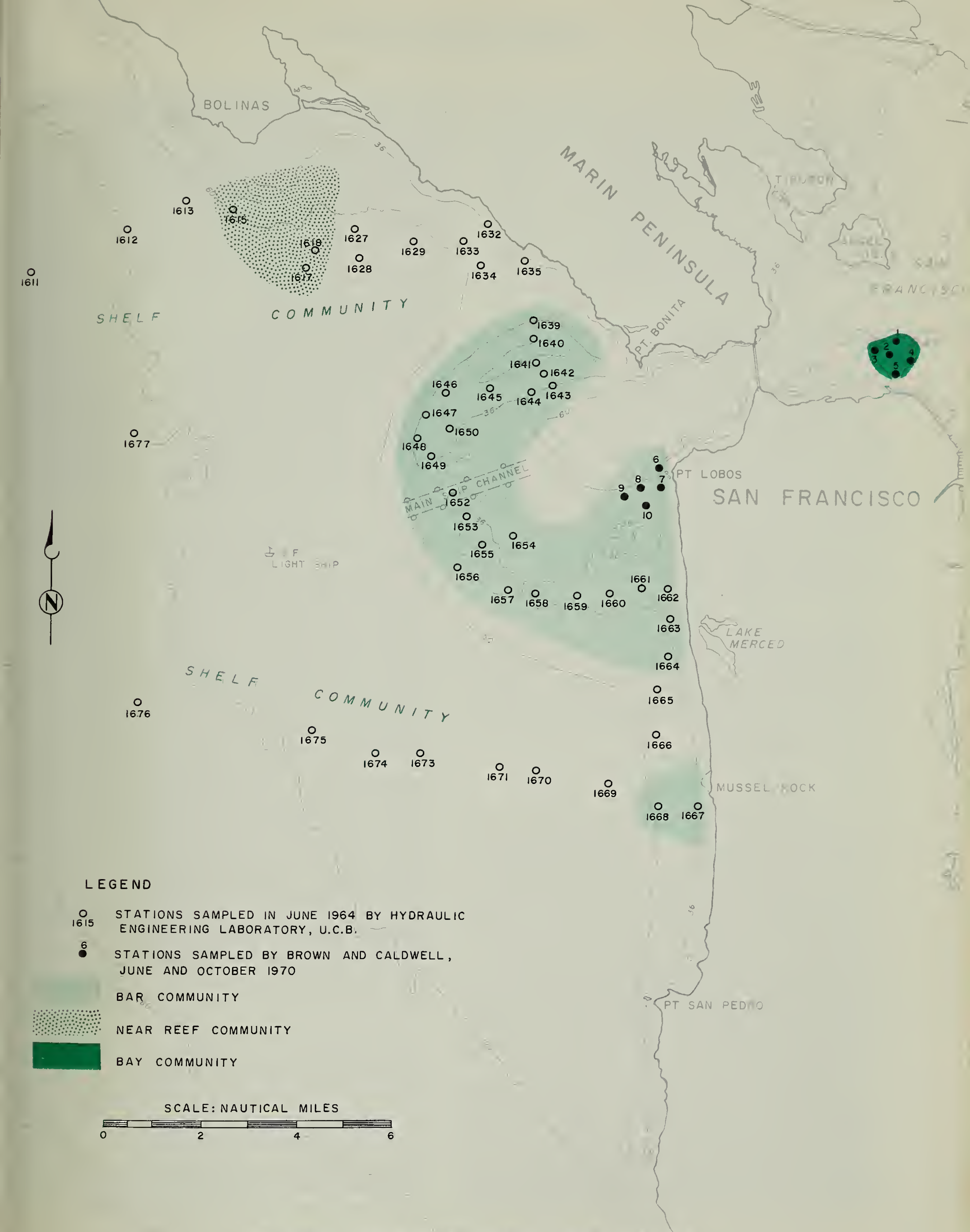


Fig. 5-27 Location of Benthic Sampling Stations and Community Types

Table 5-6 Yearly Average Values of Physical Parameters at Plankton Stations

Station location		Number per cubic meter	Diversity index (∂)	Temperature, degrees C	Salinity, parts per thousand	Density, (σ_t)
Ocean	2 meters	3,080	1.07	11.1	33.25	24.49
	10 meters	2,398	1.18	10.1	33.77	25.99
Bar	2 meters	1,529	1.34	12.8	31.29	23.56
	10 meters	4,593	1.46	11.9	32.59	24.56

scale with the magnitude of the adult population. The importance of Dungeness crab to the San Francisco fishery suggests that a more comprehensive plankton survey should be conducted.

Frequent fluctuations in plankton numbers and diversities appeared during the sampling program. Many of these fluctuations could be correlated to changes in the physical environment. The upwelling period and the fresh water runoff periods were the major phenomena influencing plankton populations. During the periods of upwelling the ocean stations exhibited a shift in predominant species and an increase in plankton numbers. During high fresh water runoff the nonmotile plankters became scarce and there was consequently a reduced species diversity. During much of the year copepods were the most important members of the zooplankton. Other organisms such as *Noctiluca*, fish eggs, salps, larvaceans, barnacles and crab zoea other than *Cancer* were occasionally dominant.

Benthic Studies

Benthic organisms are those life forms which grow on or in the bottom materials in an aquatic environment. Because of their habitat they are either stationary or much less mobile than the free-swimming and floating organisms which inhabit the water mass. Their lack of mobility makes them subject over much or all of their life cycle to the environmental characteristics at a single geographic location. For this reason benthic organisms are generally regarded as effective indicators of environmental stress, and a number of observers have used them as an index for water pollution.[38, 41, 43, 44]

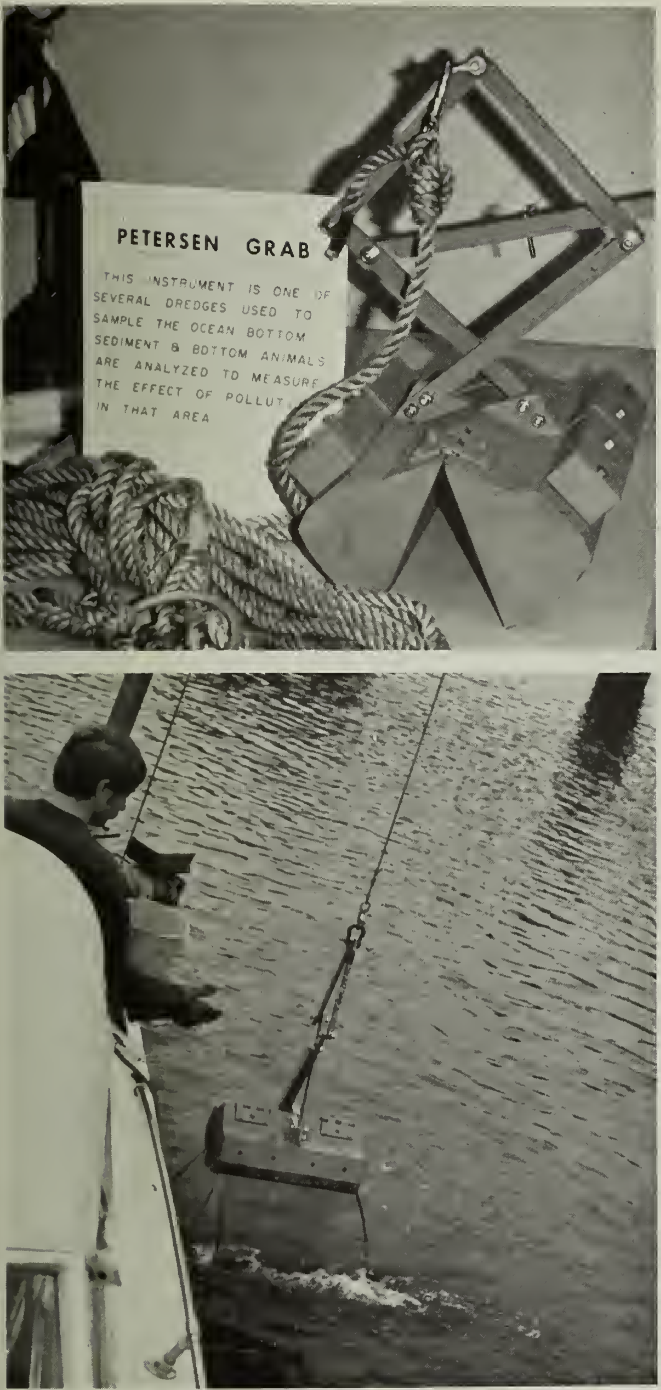
The objectives of the benthic studies was the establishment of present background conditions for benthic organisms in those areas of San Francisco Bay and the Gulf of the Farallones most subject to influence by marine waste disposal from the City of San Francisco. Once the background condition has been established, the probable effect of a waste disposal plan on the benthos can be predicted and a monitoring program can be devised to verify the accuracy of the predictions.

The benthic samples analyzed in this study came from two sources. The largest collection consisted of preserved samples that were taken in June, 1964, by the Hydraulic Engineering Laboratory of the University of California at Berkeley in connection with a major sediment study of the Gulf of the Farallones.[75] The second source was a benthic collection taken by Brown and Caldwell on cruises in the Gulf of the Farallones and San Francisco Bay during 1970.

Methods and Materials. The benthic samples collected by the Hydraulic Engineering Laboratory were obtained by towing a pipe dredge, 3-ft long and 6-in. diameter, along the surface of the bottom. The tow was usually from 100 to 200 yards and produced from one to two quarts of sample. After collection, the samples were dried and stored. These dry-preserved samples were later made available for analysis. During drying some organic matter was undoubtedly lost, but the major fraction, consisting of shell and shell fragments, was still available for analysis. Location of the sampling stations is indicated in Fig. 5-17.

Analytical preparation of the H. E. L. collection consisted of sifting the majority of organic material from the smaller sized sediment fraction. For each sample the recognizable organic parts were then separated and identified. The percentage of organic material in the sample was also tabulated on a weight basis. This calculation was determined to be the best measure of productivity available from dried samples even though large errors could be produced by currents moving shell parts into the area of the sample station and by the loss of soft-bodied organisms in the drying process.

The benthic samples obtained by Brown and Caldwell were collected with either a half-meter Peterson dredge or an orange peel dredge at the locations shown in Fig. 5-27. A minimum of two grabs was taken at each station in order to obtain



A Petersen dredge was one of the devices used for the collection of benthic samples.

a composite sample. The grab samples were individually preserved in the field using 80 percent ethyl alcohol. When returned to the laboratory, the samples were processed by washing each grab through a standard series of graded soil screens. The soft-bodied organisms and shells were identified and the remaining sediment categorized by sand-silt-clay fraction.

Representative organisms from both collections were compared to the collections of the Department of Paleontology of the University of California, Berkeley and the Department of Geology of the California Academy of Science to insure proper identification.

Benthic Community Analysis. The data from both benthic collections were combined for analysis. Because of the different sampling and preservation techniques of the two collections, comparisons of population numbers and productivity could only be approximated. Estimates from the alcohol-preserved samples were made concerning the number and weight of the soft-bodied organisms in comparison to the shell fraction. Although the soft-bodied organisms varied greatly, in most samples their weight was less than ten percent of the total organic fraction. The soft-bodied organisms contribution to the number of species was considerably greater, however, and they usually composed 25 to 50 percent of the total. As expected, the contribution of soft-bodied organisms to the benthic population was usually the highest at stations that contained large amounts of silt and clay.

The fauna from these collections demonstrated that four general benthic communities could be defined on the basis of their dominant taxa, diversity, productivity, substrate and location. These communities are identified as Shelf, Near Reef, Bar and Bay after their general locations. The extent of each community (Fig. 5-27) appeared to be controlled principally by bottom sediment type and by the amount of exposure to wave action and current. Quite obviously, Fig. 5-27 does not show the full extent of the four communities within the Gulf of the Farallones and San Francisco Bay, but rather shows the distribution by community for the benthic samples which were available for analysis. A complete analysis of each sample is presented in Volume 2, Data Supplement.

The Bay community was defined entirely from the Brown and Caldwell collection. At this community the composition of the sediments was very irregular and the bottom appeared to be a mottled pattern of different sediment types. Most of the sediments did, however, have a high fraction of mud or silt. This area was not subject to wave action but did have moderate to high current velocities. Three invertebrate groups composed over 75 percent of the organisms collected. These groups were the polychaetes (segmented worms), phoronids (chitinous tube worms) and amphipods (malacostracan crustaceans). Many of the polychaetes undoubtedly would not have been identified in dryed sample because of their soft bodies. The fact that certain phoronids were plentiful indicates that sedimentation or bottom shifting is a relatively slow process in the area sampled. These organisms are restricted in movement and could not survive on a rapidly changing bottom. The fact that most of the organisms identified were filter feeders further demonstrates that the area is not subject to a rapidly changing bottom. Higher sedimentation would clog the filtering apparatus of these organisms and make feeding impossible.

The Near Reef community occurred in sediments adjacent to shallow rocky bottoms which were subjected to heavy wave agitation. All samples of this community came from stations in the vicinity of Duxbury Reef just south of the Bolinas Peninsula. This community contained the highest diversity of fauna and the highest average productivity of all communities identified. The majority of organisms were bivalve and gastropod molluscs. The amount of shell material was high and usually composed from one-half to two percent of the total sample weight.

The Shelf community comprised those organisms which inhabit the finer grained sediments outside the bar at the mouth of the Golden Gate. The entire community is located in water depths greater than 50 ft, where the effect of wave agitation and currents is minimal. This community had the lowest standing crop, usually measuring less than one-half of one percent organic material. The major organisms were forams, especially *Elphidiella hammai*, arthropods, and small molluscs.

The Bar community was found on the San Francisco Bar at depths of 50 ft or less and was identified from both H. E. L. and Brown and Caldwell collections. The sediment of this community contained a high percentage of coarse sand, indicating exposure to moderate to strong currents and wave action. The benthos included an abundance of the sand dollar, *Dendraster excentricus*, small barnacles, *Balanus* sp., and molluscs, especially *Spisula* sp., *Tellina* sp., and *Olivella* sp. Productivity on the bar was variable, ranging from less than one-half of one percent to over two percent organic material. High productivity was usually the result of the presence of large numbers of sand dollars.

Distribution of Juvenile Cancer Crabs. An important part of the benthic analysis was planned to be the identification from shell fragments of abundance and distribution of Dungeness crab within the Gulf of the Farallones. Almost all of the crab parts that were identified in the benthic samples were observed to be juveniles. It is possible that most of these shells were deposited during the early molts. It proved impossible in many samples to identify the shell fragments of juveniles to species. Often, only a small portion of the shell was available for identification or the shell was weathered by sand abrasion beyond recognition. For this reason, it was possible only to report the distribution of juveniles from the genus, *Cancer* (Fig. 5-28).

The number of juvenile *Cancer* crabs identified was small in all samples analyzed. At most stations which contained *Cancer* shell fragments only one crab was counted, and in no sample were fragments from more than five crabs found.

The largest *Cancer* population was identified from samples in the Near Reef community (Fig. 5-28). It was likely, however, that most of these crabs were not *C. magister* but were *C. productus* or *C. antenarius*, which are often associated with rocky substrates. Most of the benthic samples from the Bar community also had shell fragments from the genus, *Cancer*. In this community the largest *Cancer* population was measured at a station on the north side of San Francisco Bar.

Benthic Studies Summary. Of the four defined communities, the Near Reef community had the highest benthic diversity and productivity. The community undoubtedly was influenced by nearby Duxbury Reef and had the highest wave agitation of the communities studied. The Shelf community had the lowest diversity and productivity of the four communities. Practically no wave agitation was present and current action was small. The Bar community was characterized by changing conditions of wave action, currents, predominant taxa and productivity. The Bay community had low diversity and was characterized by high mud and silt fractions in the sediment.

Few economically important species were identified from the benthic samples. The distribution of juveniles from the genus, *Cancer*, was reported. Almost all juvenile *Cancer* crabs came from the Near Reef and Bar communities. Even in these communities, however, the number of crabs identified was small. The Bay community had high numbers of polychaetes and phoronids. The Bar community was characterized by an abundance of sand dollars. The Shelf and Near Reef communities were dominated by forams and molluscs.

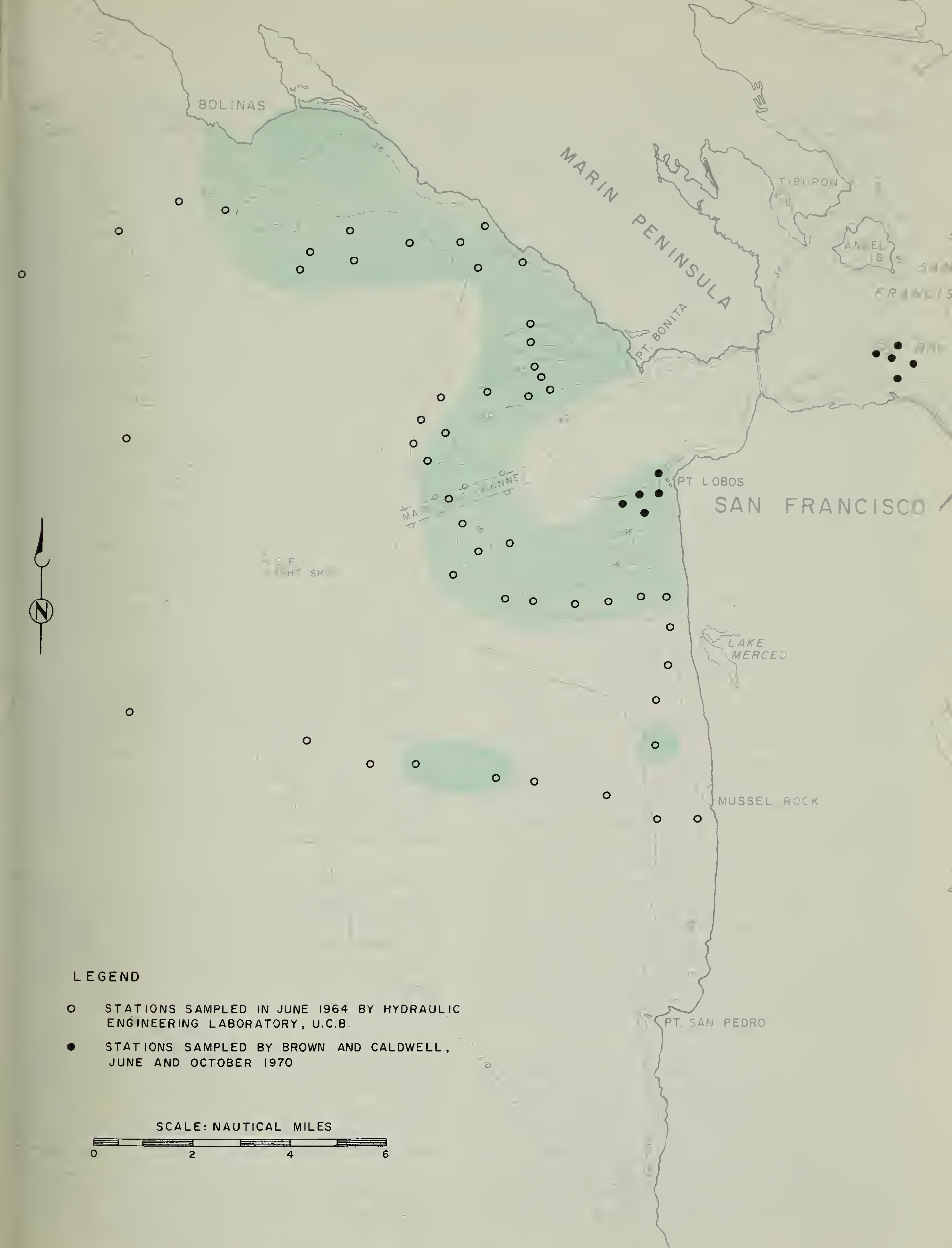

BOLINAS
MARIN PENINSULA
TIBURON
ANGEL IS
PT. BONITA
PT LOBOS
SAN FRANCISCO
LAKE MERCED
MUSSEL ROCK
PT. SAN PEDRO
N
LEGEND
○ STATIONS SAMPLED IN JUNE 1964 BY HYDRAULIC ENGINEERING LABORATORY, U.C.B.
● STATIONS SAMPLED BY BROWN AND CALDWELL, JUNE AND OCTOBER 1970
SCALE: NAUTICAL MILES
0
2
4
6

Fig. 5-28 Distribution of Stations Which Included Juvenile Cancer Crabs

Diving Studies

Diving surveys, performed by trained biologists in scuba gear, are a valuable method of collecting biological information. A visual inspection of bottom conditions not only provides new information, but aids in the interpretation of benthic sampling surveys. Diving studies were conducted during 1970 by biologist-divers from Marine Biological Consultants, Inc., of Corona del Mar, California, to evaluate the marine biota at specific locations in San Francisco Bay and the Gulf of the Farallones. Information was obtained from various locations to measure the effect of existing effluent fields on the marine environment and to obtain background data for future studies or monitoring programs.

Stations and Dates. Four nearshore locations were sampled by divers during 1970 (Fig. 5-29). The sediment and pilings around Piers 33 and 35 were studied on April 23, 1970, in connection with and investigation to study the effects of the discharge from the North Point Water Pollution Control Plant. The present outfall from the North Point plant discharges into San Francisco Bay at the ends of Piers 33 and 35. The other three locations, at Lands End, Point Bonita and an area north of Muir Beach, were studied on October 8, 1970. These later stations were chosen to evaluate the effect of the Richmond-Sunset Water Pollution Control Plant discharge on the marine environment and to gather background information from oceanic and bay locations. The Lands End study area was located directly offshore from the Richmond-Sunset outfall. The Point Bonita station was analyzed because it was influenced by amounts of fresh water and wave agitation similar to the Lands End station but was not affected by an adjacent effluent discharge. The Muir Beach sample location was studied as a more representative ocean environment for comparison with both the Lands End and Point Bonita areas. At Muir Beach wave agitation was similar to the Golden Gate stations but the environmental effect of fresh water was greatly reduced.

Methods. Diving studies were conducted by two or three biologist-divers using conventional scuba equipment. Diving was performed from a boat anchored offshore of the selected station. Weather conditions and tidal currents determined the time and exact location of each dive. At piers 33 and 35 and at Lands End diving could be conducted only during periods of low tidal current and minimum wave agitation.

Each diving study consisted of cataloging the biota along a measured transect and making general area observations and collections. The studied transect ran from the survey boat towards shore and varied in length at each site, depending upon bottom conditions, water depths, currents and wave action. Two divers swam each transect, making underwater notes of the general physical environment and compiling species lists. Unidentified species were collected in plastic bags and returned to the Marine Biological Consultants, Inc., laboratory for analysis. Representative species were compared with collections in the California Institute of Technology Kerckhoff Laboratory and Stanford University Hopkins Marine Station.

Sediment collections were obtained from sites located along the transect line and from distinct benthic communities found in the general sample area. The samples were collected in plastic bags and returned to the laboratory where they were sifted through a 0.5 mm screen. The larger organisms were identified and the sediment composition was noted. This information was combined with the field observations of sedimentation, sludge deposition and current velocities for analysis of the benthic environment at each station.

General area observations and collections were often limited by a lack of visibility. This was particularly true at the Piers 33 and 35 and Lands End stations, where the visibility was frequently less than six inches. At the other ocean stations visibility was greater and occasionally exceeded twenty feet. The nearshore location of each station and the associated wave action, however, kept the water turbid in most sample areas.

Diving Study Results. Table 5-7 presents the number of species in major taxonomic groups found at each diving location. Complete reports of the studies made by the Marine Biological Consultants, Inc., are included in Volume 2, Data Supplement. Only summaries of their findings are included here.

Piers 33-35. Extremely turbid water at this site prevented any general observations below a depth of five feet. Piling communities at different distances from the North Point outfall were examined along each pier and sediment collections were made between the piers and at offshore sites.

A total of 44 species or distinct groups were observed within the study area. At the sample sites directly adjacent to the outfalls very few species or numbers of organisms were found, and

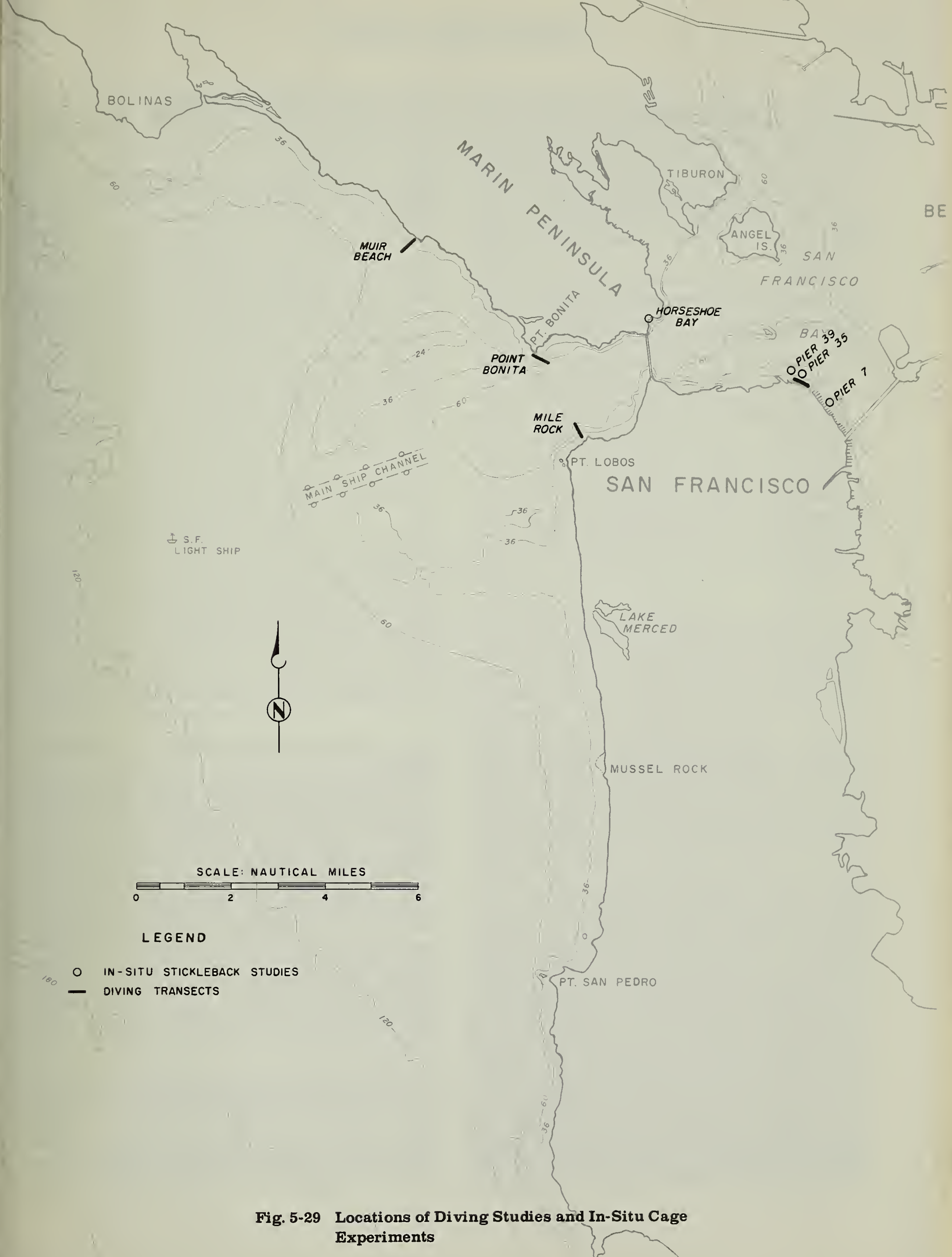


Fig. 5-29 Locations of Diving Studies and In-Situ Cage Experiments

Table 5-7 Numbers of Species (or Presumed Species) at Each Diving Station

		Number of species			
Phylum or group	Piers 33-35	Lands End	Point Bonita	Muir Beach	Total number of species, all stations
Plants					
Chlorophyta	2	1	-	-	2
Phaeophyta	-	2	4	3	9
Rhodophyta	-	7	13	21	30
Spermatophyta	-	-	1	-	1
Total plants	2	10	18	24	42
Animals					
Protoza	2	-	3	6	8
Porifera	-	1	6	14	16
Cnidaria	2	10	10	14	22
Platyhelminthes	-	-	1	1	1
Nemertea	2	1	3	2	5
Phoronida	-	1	1	-	1
Bryozoa	-	4	8	9	15
Nematoda	2	1	1	1	3
Sipunculoidea	1	1	-	1	1
Annelida	5	22	18	29	46
Arthropoda	19	25	31	49	69
Mollusca	8	17	31	25	61
Echinodermata	1	7	9	9	16
Ascidiacea	-	3	1	7	7
Vertebrata	1	9	16	8	22
Total animals	42	102	139	175	293
Total plants plus animals	44	112	157	199	335
Percent plants	5	9	11	12	13

the pilings were covered with a slick grey sediment. Here, only a few barnacles, *Balanus* sp. or *Chthamalus* sp., and unidentified insect larvae were observed. At the middle sample stations along Piers 33 and 35 the species diversity and numbers were greater and approached diversities at other bay piling communities. The green algae, *Enteromorpha* and *Ulva*, along with several species of barnacles and limpets, were most abundant on the pilings. No organisms, however, were found on the pilings below ten feet. Little or no sediment was observed on the pilings at these mid-pier stations. The stations at the intersection of the piers with the shore were most distant from the outfalls. At these sites the littoral areas also had abundant *Ulva* and *Enteromorpha*, and the general biota was quite similar to the mid-pier stations. No organisms were observed below ten feet, and the lower reaches of the pilings were covered with a thin layer of gray sediment. The presence of sediment on the pilings at the inshore stations and not at the mid-pier stations was probably the result of reduced currents in the shallow waters, which allowed settling of suspended material.

Five sediment collections were made in the sampling area within 200 ft of the outfalls. The collections made directly adjacent to the outfalls had a low species diversity and contained only testate protozoa, *Gromia* sp., peanut worms, and a few clams, *Tellina* sp. or *Cryptomya* sp. At the more distant sample locations the diversity increased with the addition of various polychaetes, harpacticoid copepods and nematodes. Sediment at all stations was composed largely of medium grained sand. The lack of sludge in the sediment and the relative diversity of the bottom infauna were attributed to moderate tidal flushing in the area.

Lands End. The Lands End area during the survey period was exposed to violent water movements from large swells and surf, a condition typical for the area. Underwater visibility ranged from 10 to 20 feet at the offshore end of the transect down to one foot or less near the shoreline.

A 2000-ft long transect perpendicular to shore directly off the Richmond-Sunset outfall was surveyed. The transect line was located from 70 ft depth to the intertidal. The survey area was primarily a sedimentary bottom with silt and fine sand in the deepest sites and coarse sand at depths shallower than 15 ft. The sediment was interspersed with a few shells and cobbles in deep areas and rock outcroppings at the nearshore sites.

The survey recovered ten plant species and 102 animal species or major groupings. All plants present were found at water depths less than 10 ft. *Ulva*, *Laminaria*, *Endocladia* and *Alaria* were some of the major algal genera present. Turbid bay water, wave agitation and effluent turbidity accounted for both a reduced algal diversity and narrow vertical distribution of the flora. Most of the collected algae came from an intertidal shipwreck in the area, and it was noted that the reduced availability of solid surfaces along the Lands End transect line also contributed significantly to the scarcity of plants.

All principal phyla or other taxa were well represented at the Lands End station except for protozoa and porifera. The largest numbers of organisms present were polychaetes, barnacles, amphipods or pelecypods. In the immediate vicinity of the outfall the faunal species diversity was reduced, but returned to background levels within 100 ft of the shore. Laterally, the influence of the outfall was confined to approximately 50 ft on each side of the transect line.

Point Bonita. The survey area was located almost entirely within the lee of the Point Bonita headland. The transect studied was approximately 500 ft long and was located in depths ranging from 35 ft to the intertidal. Underwater visibility ranged from 5 to 15 ft. The bottom was primarily rock interspersed with sand aggregates. Bottom topography was quite uneven, and ridges, pinnacles and crevices were common. Thin layers of silt covered most of the deeper surfaces.

The area yielded 18 plant and 139 animal species. A substantial fraction of the deeper rocky surfaces did not support animal encrustations, perhaps because of siltation. Attached plants, such as *Laminaria*, were abundant at depths less than 15 ft. Of the animals collected or observed various species of amphipods and annelids were the most abundant. Point Bontia also yielded the largest numbers of observed fish species.

Muir Beach. The Muir Beach transect was located just north of the Muir Cove headlands. The transect was about 200 ft long and extended up the steep slope of an islet from a depth of 40 ft to the intertidal. Topography was very irregular and the bottom consisted entirely of rocky substrate. An offshore spot dive at a 60 ft depth was also made. At this location the bottom was flat and sandy with visibility of 10 to 20 ft. The general physical environment was very similar to Point Bonita.

Recoveries from the Muir Beach area totaled 24 plant and 175 animal species. Plant life dominated to depths of about 15 ft and disappeared at about 25 ft. The transect yielded more animal species than any other location. Although the substrate was similar to Point Bonita, the higher animal diversity may have been due to the lack of influence from fresh water. When bay water runoff meets ocean waters there is typically a reduction in the number of species. This is accounted for by the lack of tolerance exhibited by purely salt or fresh water species. Unusually large numbers of rhodophyta, porifera and arthropods were unique to Muir Beach. However, species similar to those found at Point Bonita were predominant.

Diving Studies Summary. The Muir Beach transect yielded more species of plants and animals than any other station. Point Bonita had 80 percent of the Muir Beach totals, Lands End about 60 percent and Piers 33 and 35 about 15 percent. Undoubtedly the difference between substrate types available accounted for the major difference in species between the Pier 33-35 station and the other stations. A substantial number of species occurred at Muir Beach and Point Bonita but not elsewhere. A modest number of species (21) was shared by Muir Beach, Point Bonita and Lands End (Table 5-8).

It was concluded that all three ocean stations displayed a well-developed faunal composition but that the flora was somewhat deficient, probably because turbidity restricted it to quite shallow waters. Proximity to San Francisco Bay may have depressed species totals moderately at Point Bonita and Lands End. The effect of the Richmond-Sunset outfall at Lands End was very localized and resulted in little or no reduction of subtidal species diversity. The Piers 33-35 station was affected by the North Point effluent within 200 ft of the outfall, but the major cause of species reduction in the area was undoubtedly the lack of rocky substrate for plant and animal attachment. Sedimentation inshore, high turbidity and tidal

Table 5-8 **Numbers of Species Unique to Each Diving Station or Shared by Various Combinations of Stations**

Phylum or group[a]	No. of species unique to each station[b]				No. of species common to two stations[b]						No. of species common to three stations[b]				No. of species common to all stations[b]
	A	B	C	D	AB	AC	AD	BC	BD	CD	ABC	ABD	ACD	BCD	
Plants															
Chlorophyta	1				1										
Phaeophyta			1	1				1		1					
Rhodophyta		2	2	10				1		6				1	
Total plants	1	2	4	11	1			2		7				1	
Animals															
Protozoa			1	4			1								
Porofera		9								5					
Cnidaria		3						1	4	5				1	
Phoronida								1							
Bryozoa		3	2	4				1		3					
Annelida	5	10	3	10	1			1	3	5			1	3	
Arthropoda	7	4	2	16				2	1	7	1	1		10	2
Mollusca	6	7	17	15				4	1	4	2			1	1
Echinodermata		5	2	1						5				2	
Ascidiacea		2	1	5					1						
Vertebrata		3	9	1				1		3				3	
Total animals	18	34	43	68	1		1	11	10	37	3	1	1	20	3
Total plants plus animals	19	36	47	79	2		1	12	10	44	3	1	1	21	3
Percent unique species	43	32	31	39											

[a] Only organisms identified to species were employed for this tabulation.

[b] Diving sampling stations (see Fig. 5-29): A, Piers 33-35; B, Lands End; C, Point Bonita; D, Muir Beach.

surge at the end of the piers was also responsible for a low species diversity.

Intertidal Studies

Intertidal biota consists of plants and animals that live on a variety of substrates between the lowest low tide level and the upper splash zone. Some of these organisms are subjected daily to alternate periods of submergence and drying, while other organisms are only submerged or air exposed during periods of extremely high or low tides. These extreme tides might occur only once a month. The wide range of environmental conditions results in a great diversity of organisms inhabiting the intertidal zone.

A large number of distinct physical environments are found in the intertidal zone. Sandy ocean beaches, mud flats, reefs and rocky tide pool areas are a few of the more common types. The intertidal areas, because of their accessibility, beauty and interest, and the most heavily used for recreational purposes of any of the marine associated environments. Because of this popularity and the importance of the intertidal zone to the total marine environment, it is important that the intertidal zone be protected from the detrimental effects of waste discharges.

The intertidal investigations reported in this study were designed to survey both oceanic and bay-influenced locations. Information concerning the types and diversity of intertidal biota was collected at each site. These data were obtained for use as background material for future monitoring and research studies. The surveys were also designed to measure the effect of an existing municipal waste discharge on the intertidal biota.

Stations and Dates. Seven intertidal areas were investigated during 1970 (Fig. 5-30). The areas were chosen because of their location, biota, substrate or association with an existing waste discharge. All stations were sampled in November and December, 1970, with the excep-

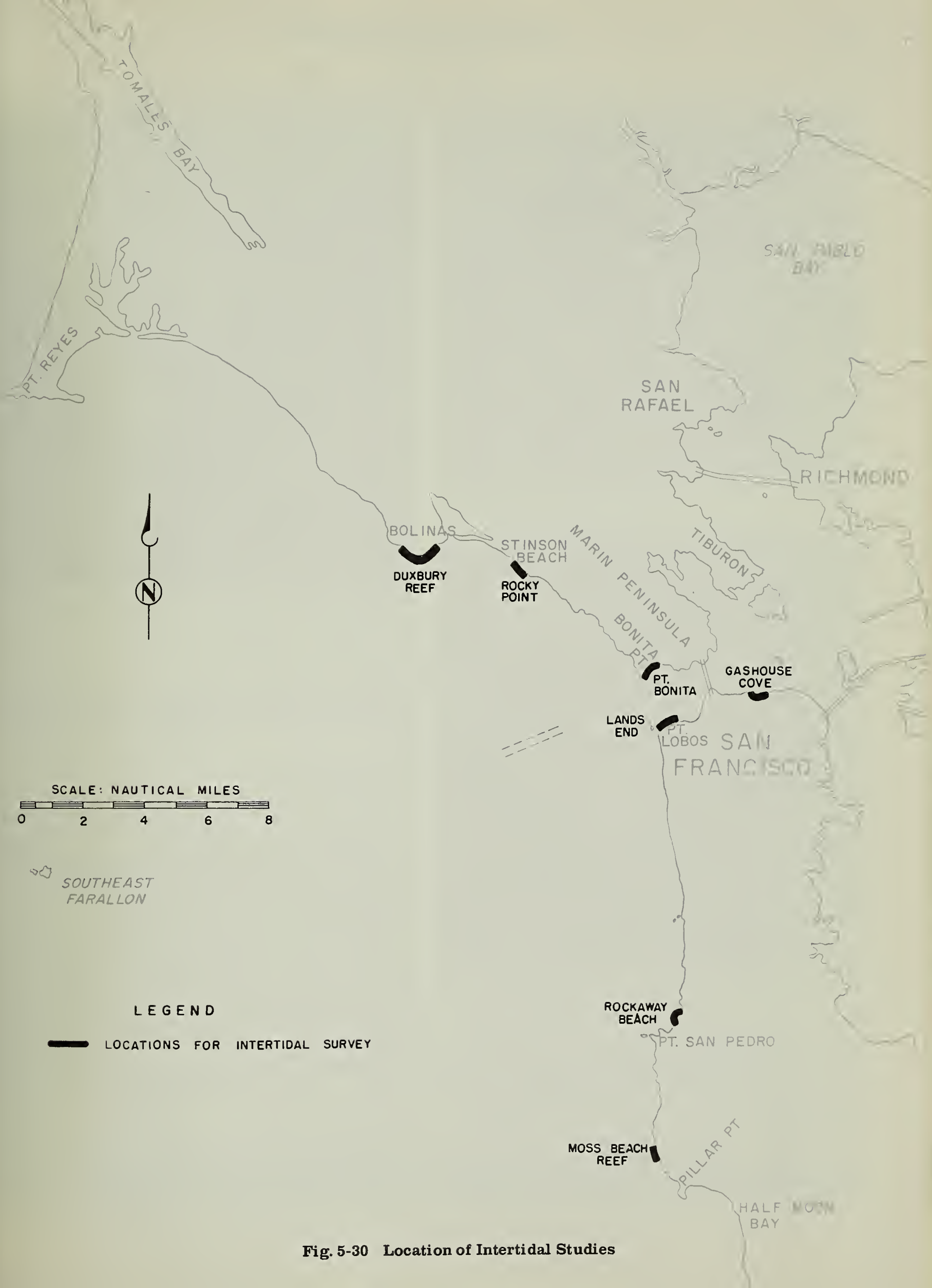


Fig. 5-30 Location of Intertidal Studies

tion of the Gashouse Cove location, which was studied in October. Three of the stations, Lands End, Duxbury Reef and Point Bonita, were also surveyed in the summer. Following is a list of the intertidal survey areas, a brief description of their physical environment and the reasons for including each location in the study program.

Gashouse Cove. This study area is located in a small boat harbor adjacent to Fort Mason on the south shore of Central San Francisco Bay. Intertidal surveys in the area included an examination of the floats, docks and rock breakwater regions for flora and fauna diversity. The location was surveyed because it was representative of environments within the Central Bay.

Lands End. The Lands End survey location included the rock and sand beaches directly south of the Mile Rock Lighthouse. The area was located at the foot of steep headlands and included the shoreward portions of the Lands End diving study reported previously. Biota at this location was exposed to influence of low salinity outflow from San Francisco Bay, marine water from the Gulf of the Farallones and a field of municipal sewage effluent. The area was surveyed because it surrounds the existing outfall from the Richmond-Sunset Water Pollution Control Plant.

Point Bonita. The Point Bonita survey area was located at the east base of the headlands on the north shore of the Golden Gate. This location is similar to Lands End in that it is exposed to mixtures of San Francisco Bay water and marine water from the Gulf of the Farallones. However, it is remote from any waste discharge. The survey area consisted of mixtures of coarse sand beaches and rock outcroppings. Point Bonita served as a background station for assessing the effects of the waste discharge at Lands End.

Rocky Point. Rocky Point is a westward land projection at the south edge of Bolinas Bay. The survey area consisted of wave-swept boulder beaches and a small sand-beached cove. The intertidal zone was studied because it is typical for ocean exposed rocky coasts north of San Francisco Bay. This location is not influenced to any appreciable extent by the outflow from San Francisco Bay.

Duxbury Reef. Duxbury Reef is reported to be the largest reef on the western coast of North America. It is located along the west and south base of Bolinas Point about 12 miles north of the Golden Gate. The survey area included the southern half of the reef. This location was studied because of its importance as a natural reserve supporting a wide variety of plants and animals. Duxbury Reef has recently been declared a state protected recreational area.

Rockaway Beach. The Rockaway Beach study area was located at the base of a rocky headland projection just north of San Pedro Point, approximately 10 miles south of the Golden Gate. The survey site consisted of wave-swept beaches and rock-sheltered tide pools. Large boulders were distributed throughout the sample area. The area was studied because it is the first large accessible rocky location south of San Francisco. It lies at about the southern limit of influence of the outflow from San Francisco Bay.

Moss Beach. This site consists of an intertidal preserve location south of Point Montara and approximately 18 miles south of the Golden Gate. The survey area included a major part of the state-protected reef environment. The site is well known for its great abundance of seaweeds and fauna. Moss Beach was studied because this location, along with Duxbury Reef, is far removed from influences of the bay and can be used as an ocean background station to assess future intertidal changes at the locations closer to the mouth of the bay.

Intertidal Study Methods

Three or more biologists cooperated in the investigation of each sample area. The intertidal sites were studied only during periods of extremely low tides (less than -0.5 ft). Each survey was begun about two hours before low water and continued through the low water period.

Most surveys consisted of compiling species lists of flora and fauna, analysis of transect lines, biota collection, general field notes, mapping of surveyed area and extensive photography. Biota lists of each area, compiled by specialists in intertidal surveys, provided a basis for comparison with historical surveys and for future monitoring studies. Transect lines were laid out from the upper splash zone to the low tide water line, and community distributions and species abundance were observed along the line. Collections were made of plants and animals throughout the survey area. Unidentified biota were collected and returned to the laboratory for analysis, and repre-

Studies of intertidal biota were carried out along a transect line extending from extreme low water to the upper splash zone.

A meter square was used to quantify the biota along the intertidal study transect lines.

sentative organisms were obtained to establish type collections. Collections were made in plastic bags, buckets and glass jars.

General field notes were made on site by the use of portable tape recorders. These recordings were directed towards noting the nature of the physical substrate, weather conditions, extent of ground cover, and a continuous record of the activities of the investigators. Detailed sketch maps were drawn for each survey area in order to insure that investigators could return to precisely the same location for future investigations. Community distribution, transect lines and locations of sampling were mapped as well as the general topography of the area. The general area, localized habitats and individual organisms were documented by 35-mm color photography. These pictures were used in conjunction with the mapping, field notes and species lists to present a detailed analysis of each study area.

Intertidal Study Results

The complete analysis of each intertidal survey is presented in Volume 2, Data Supplement. Comparisons between the various areas and the effect of the existing Richmond-Sunset discharge on the intertidal biota are presented here.

Biologists engaged in intertidal studies near the water's edge wore wet suits for protection.

Physical Environments. Duxbury Reef and Moss Beach are similar in several important respects. They both are extensive shale reefs offering varying degrees of exposure to surf and warming by insolation. The strata dip sharply, and the rocks more resistant to erosion form parallel ridges which separate channels and large shallow pools left behind by the receding tide.

The headland at the southern end of Rockaway Beach presents a smaller intertidal area than either Duxbury Reef or Moss Beach, but it is sufficiently varied topographically to support a moderately diverse flora and fauna. The headland faces the sea as a rapidly eroding cliff, the base of which is strewn with sandstone boulders. The boulders are pounded nearly continuously by the waves and are not distributed in sufficient density seaward from the cliff to provide semi-protected habitats landward of the surf line. Also, small boulders insecurely lodged among the larger immovable rocks are moved about in heavy seas, grinding away much of the biota.

Point Bonita, Rocky Point and Lands End are basically similar in structure. Each is a wave-swept boulder beach supporting a biota of relatively low diversity and luxuriance. At Point Bonita and Lands End the boulders are intermixed with gravel and some coarse sand. The gravel scours the intertidal rocks quite clean in certain areas, but in other places, particularly at Point Bonita, the rocks support a fairly heavy growth of a rather small number of species. The north side of Rocky Point includes a semi-sheltered medium grained sandy beach with scattered large partially-buried rock outcroppings.

The Gashouse Cove site is an enclosed area which is protected from wind and waves by a breakwater. All of the sites studied at this location were man-made, such as docks, piers and the rocks of the breakwater.

Flora. Duxbury Reef and Moss Beach exhibited the greatest diversity and most luxuriant growth of seaweeds of all the sites studied. These two sites rank with Point St. George, northwest of Crescent City, and the Monterey Peninsula in exhibiting the greatest abundance and diversity of seaweeds to be found along the central and northern California coast. The richness of the flora at these two locations has been recognized by marine biologists for many years and is amply documented by frequent sampling extending back to 1895. The number of species of macroscopic seaweeds at either location totals about 120 for the year, though not all will be found at any one time. The mid-littoral turf is a complex association of many species belonging to the green, brown and red algal taxonomic groups. The lower littoral is dominated by bulky kelps, which tend to obscure the great diversity of red algae at that level.

The flora of Rockaway Beach is moderately diverse and resembles that of Moss Beach and Duxbury Reef, but the nature of the unprotected environment results in the elimination of many species that require the protection of large reefs.

At Point Bonita and Rocky Point the mid-tidal turf is similar in composition to that of most central and northern California localities but is neither as luxuriant nor as diverse. Rocky Point, for reasons not apparent, supported even a less luxuriant flora than Point Bonita, and except for the fact that there is a single tide pool left behind at extreme low tide which harbors several unique species, its diversity would also be less. A factor in the apparent low diversity was undoubtedly the inhospitable nature of the site, which precludes extensive shore collecting in the lowest littoral.

Lands End was the only locality where the effect of a sewage effluent field was observed. Here the seaweeds presented the typical syndrome of high organic loadings: decreased diversity accompanied by enhanced development of certain species and stunted development of others. Within 50 ft of the outfall the intertidal rocks were devoid of macroscopic algae. From 50 to 400 feet from the outfall towards Fort Point the intertidal rocks become increasingly populated, but at best the number of conspicuous species was strikingly small. The dominance and luxuriance of the red alga, *Prionitis* in the mid-tidal zone and of the kelp *Laminaria sinclarii* in the lower littoral was notable. At the zero tide level *Ahnfeltia plicata* was surprisingly abundant. Only six other species were observed in the mid-tidal zone, with a few others in the upper littoral.

Gashouse Cove supported 12 species of macroscopic algae on the rock jetty and wood docks. No species were particularly luxuriant, however. The extremely different environment at this location gave little basis for comparisons with other stations.

Fauna. Moss Beach and Duxbury Reef support a large diversity and luxuriance of animal as well as plant populations. In the reef habitats crabs, barnacles, bryozoans, isopods, anemones and sea urchins were particularly abundant. The deeper tide pools also supported a variety of fish such as rockfish and sculpins.

The Point Bonita, Rocky Point and Rockaway Beach locations were considerably more restricted in size and habitat type. The same species that were predominant at the two reef stations were also most abundant at these locations, but many of the less abundant species were absent. The exposure to wind and surf at these locations allowed only attached species such as the mussels, barnacles and chitons to exist in large numbers.

A total of 46 species or distinct groups of animals were identified at Lands End. Species number and diversity of animals were reduced in the immediate vicinity of the outfall. The abundance of fauna increased rapidly with distance from the outfall until at 400 ft to the east or 100 ft to the west the intertidal biota appeared normal in composition and diversity. The predominant onshore winds and waves tend to keep the effluent field concentrated along the shore, but strong tidal currents appeared to provide a high degree of dilution within a short distance from the outfall.

At Gashouse Cove 23 animal species were identified during the survey. The area supported fewer animals than the other localities, but this was undoubtedly a result of the limited substrate types and the lack of purely oceanic species. Barnacles, amphipods, gastropods and mussels were the most abundant of the species found at this site.

Intertidal Study Summary

Information concerning the intertidal biota at seven locations was collected and analyzed. Of the areas studied Moss Beach and Duxbury Reef supported the greatest diversity and abundance of plants and animals. The other locations exhibited a more restricted biota, primarily because of limited substrate type and availability and because of the lack of protection from surf and weathering.

The Lands End station was also investigated in order to assess the influence of the existing Richmond-Sunset outfall on the intertidal biota. Within the immediate area of the discharge there was a significant reduction in biota numbers and luxuriance, but recovery to normal abundance and diversity was rapid with distance from the outfall. The influence of the outfall could not be observed greater than 400 ft from the point of discharge. The general impoverishment of the flora at Lands End cannot be blamed entirely on the sewage outfall, however. Records in the University of California Herbarium at Berkeley dating back to 1896 show that the flora of this locality before the outfall was installed was basically similar to the flora studied, with only a few species not currently found there. Then, as now, it seemed to be a badly battered spot inhospitable to seaweeds. Changing salinity resulting from the ebb and flow of tides through the Golden Gate is undoubtedly an important factor, as indicated by the fact that a similar depression in diversity was observed at Point Bonita.

In Situ Bioassays

To complement the controlled toxicity experiments at the Ft. Baker laboratory an attempt was made to assess the actual toxicity of an existing effluent discharge in San Francisco Bay. Cages of fish were placed in an effluent field at various distances from the point of discharge. The North Point effluent field was selected for investigation because it is the largest discharge from the City of San Francisco and is easily accessible from numerous piers along the waterfront. In situ bioassays were conducted from April through June, 1970.

Methods and Materials. In each experiment from 12 to 25 fish were placed in cages and submerged at the test sites. The fish cages measured 3 x 4 x 1 ft and were composed of 1-in. wire screen frames. A coarse mesh (No. 2) netting was secured within the frames to form the actual fish containers. Each cage was attached to a pulley system that was anchored to the bottom with a 40-lb Danforth anchor. Surface and bottom ties were required to prevent the cages from moving in the tidal currents and wave surges. The cages were submerged approximately ten feet beneath the surface at low tide. Three-spined stickleback were used in these experiments because they were available in large numbers and have been studied extensively in routine bioassays of municipal discharges.

The fish cages were suspended from the ends of selected piers at the locations shown in Fig. 5-29. Two controls were used during the research programs: the harbormaster pier in Horseshoe Bay and Pier 7 in San Francisco Bay. Both sites were essentially outside of the North Point effluent field. The Horseshoe Bay station served as a background check on the Pier 7 site, which may have been susceptible to influence by other waste discharges within the bay.

The Pier 35 site was located directly over the North Point discharge, and the cages suspended there were influenced by the effluent field 100 percent of the time. The minimum effluent dilution at the surface had been measured at approximately

1:5 during an earlier investigation. Therefore, it was estimated that for much of the time cages suspended at Pier 35 were subjected to dilutions between 1:5 and 1:20.

The Pier 39 test site was located seaward from Pier 35 and therefore was in the effluent field only during the ebbing tide. It was estimated that cages at this site were in the effluent field approximately 50 percent of the time. As described in Chapter 4, the effluent dilution at this site was measured to be always greater than 1:200.

In Situ Bioassay Results. The results of the five experiments conducted are presented in Table 5-9. Field data are included in Volume 2, Data Supplement. The averages for all replicates are also calculated. The survival of three-spined stickleback was 100 percent at the Horseshoe Bay control site during each test. The survivals at all other sites varied from test to test. Survivals at the effluent test sites (Piers 35 and 39) varied from 100 percent to 26.7 percent. The low survivals, however, occurred when ships were docked at the piers. While a direct relationshio between ships and test fish survival could not be proved, reduced survival could result from several factors. Most probable factors are buffeting and stirred up bottom sediements resulting from propeller action, toxic discharges from the ships' drains and bilges and spillage of paint and hull preservatives. In all experiments the survival of test fish at the Pier 35 site, under continuous exposure to a concentrated effluent field, was equal to or greater than the survival of fish at the Pier 39 site, where the fish were exposed 50 percent of the time to a dilute effluent field.

Table 5-9 **96-hour In-Situ Stickleback Bioassays**

Experiment No.	Percent survival			
	Controls		Experiments	
	Horseshoe Bay	S.F. Bay (Pier 7)	Pier 39[a]	Pier 35[b]
1	100	[c]	67	75
2	100	[c]	93.5	93.5
3	100	[c]	60	86.8
4	100	68	26.7	26.7
5	[c]	100	100	100
Average	100	84	69.5	76.4

[a] Station exposed to North Point effluent field approximately 50 percent of the time.

[b] Station located directly in North Point effluent field at point of discharge.

[c] No data.

The average results of the five experiments show a lower test survival at all the San Francisco Bay sites than at the Horseshoe Bay control site. There also appeared to be a slightly higher mortality at the effluent exposed stations than at the Pier 7 control station. However, if the low survivals at Piers 35 and 39 for Experiment 4 are assumed to be the result of ships at the piers and are discarded, there was no significant difference in survival between Piers 7, 35 and 39. It appears, therefore, that the effluent field from the North Point discharge added no measureable toxicity, as measured by 96 hour tests, to the San Francisco Bay water. There was some evidence that the water along the San Francisco shoreline exhibits a higher toxicity than the water at Horseshoe Bay. Identification of the source or cause of the toxicity would require a program of far greater scope than could be undertaken in the course of this study.

LABORATORY INVESTIGATIONS

Laboratory investigations were conducted from February through September, 1970 at the San Francisco Bay Marine Research Center at Fort Baker, on Horseshoe Bay. Horseshoe Bay is a small cove on the northwest coast of Central San Francisco Bay near the Golden Gate. The laboratory was equipped with a continuous supply of bay water by means of a submersible centrifugal pump located beneath the Harbormaster Pier near the mouth of Horseshoe Bay. The laboratory was designed as a complete facility for research on estuarine and marine organisms. Laboratory investigations at the San Francisco Bay Marine Research Center were conducted under the direction of Brown and Caldwell, using funds supplied by the City and County of San Francisco.

The purpose of the laboratory research was the development, through controlled experiments, of quantative information on the toxicity of San Francisco sewage effluent to marine organisms. The experiments modeled the marine environments of the Gulf of the Farallones and Central San Francisco Bay. In the course of the study a variety of different marine organisms were exposed to varying concentrations of composite effluent from San Francisco's water pollution control plants. Test results enabled the assessment of the long and short term effects of municipal waste discharges on free-swimming organisms (nekton), bottom dwelling organisms (benthos), and on the zooplankton.

To assess accurately only the influence of the composite sewage effluent on the test organisms, all variables except the addition of sewage were held constant throughout the experiments. Also, all tests were conducted with a control replicate which contained no added effluent and which measured only the effect of the model environment on the test organisms.

Dilution Water

The background water used in most experiments during 1970 was supplied continuously from the submerged pumping system. The pump was coated with an epoxy-resin resistant to salt water in order to avoid exposure of metal surfaces to the background water, and water was pumped to the laboratory through polyvinylchloride pipes. In the laboratory the water was delivered directly to the experiments or diverted to a 39,000 gallon aged concrete tank. The tank served as a constantly flowing reservoir which provided an emergency supply of water in the event the submerged pump malfunctioned.

Tests of the background water indicated that it was representative of Central San Francisco Bay water and that it was not toxic to the variety of organisms tested. During the laboratory investigations the salinity in the background water varied from 20 to 28 ppt, and the temperature ranged from 12 to 16 deg C.

Sewage Effluent

The samples of effluent studied in the laboratory were collected from each of the city's three municipal waste treatment plants described in Chapter 2. In the beginning of the research program, effluent collections were made weekly at each plant. Later, collections were obtained biweekly. The day of collection was chosen randomly, and all three plants were sampled on the same day. At all plants the effluent samples were obtained directly at the point of discharge after all chemical and physical treatment had been completed, including postchlorination.

A 24-hour composite sample was collected from each treatment plant. Individual flow proportional subsamples were collected hourly and composited in a 20-gallon aged plastic container. A minimum of five gallons was collected at the Richmond-Sunset and Southeast plants, and at least ten gallons was collected at the North Point plant. The three effluent samples were then transported to the laboratory where they were mixed together in proportion to the average daily flow at each treatment plant. The usual mixture ratio was 6:2:2 for North Point, Richmond-Sunset and Southeast plants, respectively. This proportional mixture was then used as the test solution in marine and estuarine bioassays.

Effluent collections were stored in several ways during the course of the laboratory investigations. Early in the program, the composite sample was split into one gallon portions, quick frozen, and then thawed as required for experiments. Later in the program the entire composite sample was refrigerated at 4 deg C. This technique proved better in the later investigations because of the constant requirement of effluent for continuous flow experiments. In some cases, composite effluent samples were diluted 50 percent by fresh background bay water before cooling. This dilution made mixing and addition to continuous flow experiments easier. No differences in toxicity were observed between frozen and refrigerated samples during the research program.

A comprehensive chemical analysis was performed on the initial sample of composite effluent used in the bioassay program (Table 5-10). This analysis was obtained to anticipate the degree and source of possible toxicity to the marine organisms. The analysis indicated that the composite sample was typical for a municipal sewage effluent.

As was expected from the chemical analyses, subsequent bioassays indicated that the effluent was not severely toxic. In later stages of the program, therefore, chemical analyses were discontinued and one-liter subsamples were frozen for possible future analysis. Since no toxic anomalies occurred during the remainder of the study, these subsamples were not analyzed.

Test Organisms

The marine and estuarine organisms that were studied in the laboratory investigations were collected from the littoral, planktonic, pelagic and benthic communities.

Selection of Organisms. The purpose of studying a variety of marine and estuarine animals in the laboratory was to provide a basis for prediction of the effect of various dilutions of composite San Francisco sewage effluent on the total marine environment. Ideally, the goal of the study would require the testing of representative organisms from all of the different marine habitats

Table 5-10 Chemical Analysis of San Francisco Composite Sewage Effluent

Determination[a]	mg/l	Determination[a]	mg/l
Anions		Arsenic as As	0.006
Nitrite (NO_2)	0.39	Iron as Fe, by AAS	0.52
Nitrate (NO_3)	19.9	Copper as Cu, by AAS	0.19
Chloride (Cl)	425	Nickel as Ni, by AAS	<0.01
Sulfate (SO_4)	114	Chromium as Cr, by AAS	0.2
Bicarbonate (HCO_3)	150	Aluminum as Al, by AAS	0.28
Carbonate (CO_3)	0	Lead as Pb, by AAS	0.34
H. Phosphate (HPO_4)	11.1	Tin as Sn, by AAS	<0.2
H_2Phosphate (H_2PO_4)	8.9	Zinc as Zn, by AAS	0.25
		Manganese as Mn, by AAS	0.12
Cations		Silver as Ag, by AAS	<0.005
Ammonium (NH_4)	19.4	Potassium as K, by AAS	9.1
Sodium (Na)	258	Strontium as Sr, by AAS	0.31
Potassium (K)	9.1	Zirconium as Zr, by AAS	< 5
Calcium (Ca)	29	Boron as B	1.1
Magnesium (Mg)	32	Barium as Ba, by AAS	<0.05
Phenolphthalein Alkalinity ($CaCO_3$)	0	Cadmium as Cd, by AAS	<0.01
Methyl Orange Alkalinity ($CaCO_3$)	129	Lithium as Li, by AAS	<0.05
Calcium Hardness ($CaCO_3$)	72	Titanium as Ti, by AAS	<0.1
Magnesium Hardness ($CaCO_3$)	132	Bismuth as Bi, by AAS	<0.05
Total Hardness ($CaCO_3$)	204	Fluoride (F)	0.9
Total Phosphate (PO_4)	20	Dissolved Residue - Evaporated	1100
Silica (SiO_2)	12	Loss on Ignition	255
Nitrite (N)	0.12	Fixed Residue	845
Nitrate (N)	4.5	Suspended Matter, total	180
Ammonia (N)	16.0	Suspended Matter, volatile	145
Organic Nitrogen (N)	28.2	5-day BOD, 20°C	178
Total Nitrogen (N)	48.8	COD	385
Grease	30		
Turbidity, JTU	75	Pesticides, parts per billion	
Settleable matter, ml/l/hr	1.5	Chlordane	2.0
Specific Conductance[b]	1886	Aldrin	0.4
Hydrogen ion conc., pH	6.9	DDE	0.2
		Methyl parathion	2.0

[a] Sample analyzed was a 24-hour flow-proportional composite of dry weather flow collected at each of the city's three sewage treatment plants on February 20, 1970, and then composited in proportion to the total daily flow at each plant.

[b] Expressed in micromhos at 25 degrees C.

within the study area. In practice, however, the actual selection of a particular species for toxicity study was based on two criteria: first, large numbers of specimens had to be collected to obtain statistically significant results. This limited the collections to those organisms which were relatively abundant and easy to collect. Also, this requirement prohibited the use of species that could not be transported to or cultured in the laboratory because of a low tolerance to handling or to the model environment. Second, the actual habitat from which the test organism came had to be capable of being modeled in the laboratory. This prevented the use of certain large mud burrowers and many adult pelagic fish.

The total list of organisms collected is presented in Table 5-11. Many thousands of individual organisms were collected, but most species were not represented in sufficient numbers for statistical analysis of the toxicity bioassays. In the final study program 22 species were tested, which represented most of the distinct marine communities in the waters surrounding San Francisco. The analyzed species included juvenile as well as adult organisms. This provided valuable information on the response of particular species throughout their life histories. Day and night collections were made to obtain the variety of species shown.

Table 5-11 Collected Organisms, Locations and Sampling Methods

Organism	Development stage			Collection station	Collection method				
	Adult	Juvenile	Larvae		Beach seine	Throw net	Scuba and free diving	Trapping	Hand nets and digging
Vertebrates									
Penpoint gunnel Apodichthys flavidus	x			1,6	x				
Jack smelt Atherinopsis californiensis	x			6,8	x				
Mottled sand dab Citharichthys sordidus		x		6	x				
Shiner perch Cymatogaster aggregata	x	x		6,14	x			x	
Three-spined stickleback Gasterosteus aculeatus	x			6,11	x	x			
Walleye surf perch Hyperprosopon argenteum	x			6	x				
Staghorn skulpin Leptocottus armatus	x			6	x				
Ling cod Ophioden elongatus		x		6	x				
Striped bass Roccus saxatilis		x		6	x				
Skulpin Scorpaena guttata		x		6	x				
Rock bass Sebastodes sp.		x		6	x				
Pipe fish Syngnathus griseolineatus	x			6,14	x				
Invertebrates									
Pink ghost shrimp Callianassa californiensis	x			6					x
Market crab Cancer magister	x	x	x	6,9			x	x	
Rock crab Cancer antenarius	x	x		6				x	
Red crab Cancer productus	x	x		6,9			x	x	
Bay shrimp Crago sp.	x		x	6,13	x				
Sand crab Emerita analoga	x		x	2,3, 4,7					x
Shore crab Hemigraphsis oregonensis	x		x	6,14				x	x
Bent-nose clam Macoma nasuta	x	x		6					x
Bay mussel Mytilus edulis	x			1,9					x

Continued on next page

Table 5-11 Collected Organisms, Locations and Sampling Methods (Continued)

Organism	Development stage			Collection station	Collection method				
	Adult	Juvenile	Larvae		Beach seine	Throw net	Scuba and free diving	Trapping	Hand nets and digging
Invertebrates (Con'd)									
Mud snail Nassarius cossatus	x			5					x
Hermit crab Pagurus samuelis	x			1,5					x
Porcelain crab Petrolisthes cinctipes	x			1					x
Kelp crab Pugettia productus	x			9			x		
Washington clam Saxidomus nuttalli	x			9			x		x
Broken-back shrimp Spirontocaris paludicola	x		x	6,11	x	x			
Purple sea urchin Stronglocentrotus purpuratus	x			1			x		
Turban snail Tegula funebralis	x			1,5					x
Blue ghost shrimp Upogebia pugettensis	x	x		6,8					x
Ribbed horse mussel Volcella demissa	x			12					x

Collection Sites and Methods

The sampling locations included brackish and salt water environments and were situated throughout the San Francisco Bay-Delta and along the California coast as shown in Fig. 5-31. These sites were chosen for the abundance and diversity of species present and for the nature of the background water in that area. The variety of marine species sampled at each collection site is presented in Table 5-11.

To test the effect of a municipal waste discharge on the many marine communities, it was desirable to obtain both organisms that had, and those that had not, been previously exposed to effluent dilutions during their life histories. This selection of organisms was designed to preclude the possibility that natural selection would influence the result of toxicity studies by resultung in genetic strains of organisms which were more resistant to dilutions municipal waste. The collection sites in Drakes Bay, for example, provided organisms for analyses whose ancestors had likely never received significant exposure to treated municipal waste. Similar species collected in Horseshoe Bay were routinely exposed to minute dilutions of municipal waste from the many discharges into San Francisco Bay. During the course of the experiments, however, no significant difference in tolerance was noted between organisms of the same species which came from different collection sites.

Collection techniques were selected to suit the habitat being investigated and the organisms desired. A complete summary of the collection methods used is also presented in Table 5-11. Along sandy beaches and in shallow waters with gravel substrate a 1/4-inch mesh beach seine was commonly used. This technique frequently caught large numbers of juvenile and small adult fish such as shiner perch, walleye surfperch, jacksmelt and flatfish. In deeper waters and in offshore sampling a weighted throw net was occasionally used. This device provided collections of three-spined stickleback and pipefish. Scuba or free diving was also employed for benthic sampling in deep water sites. These diving

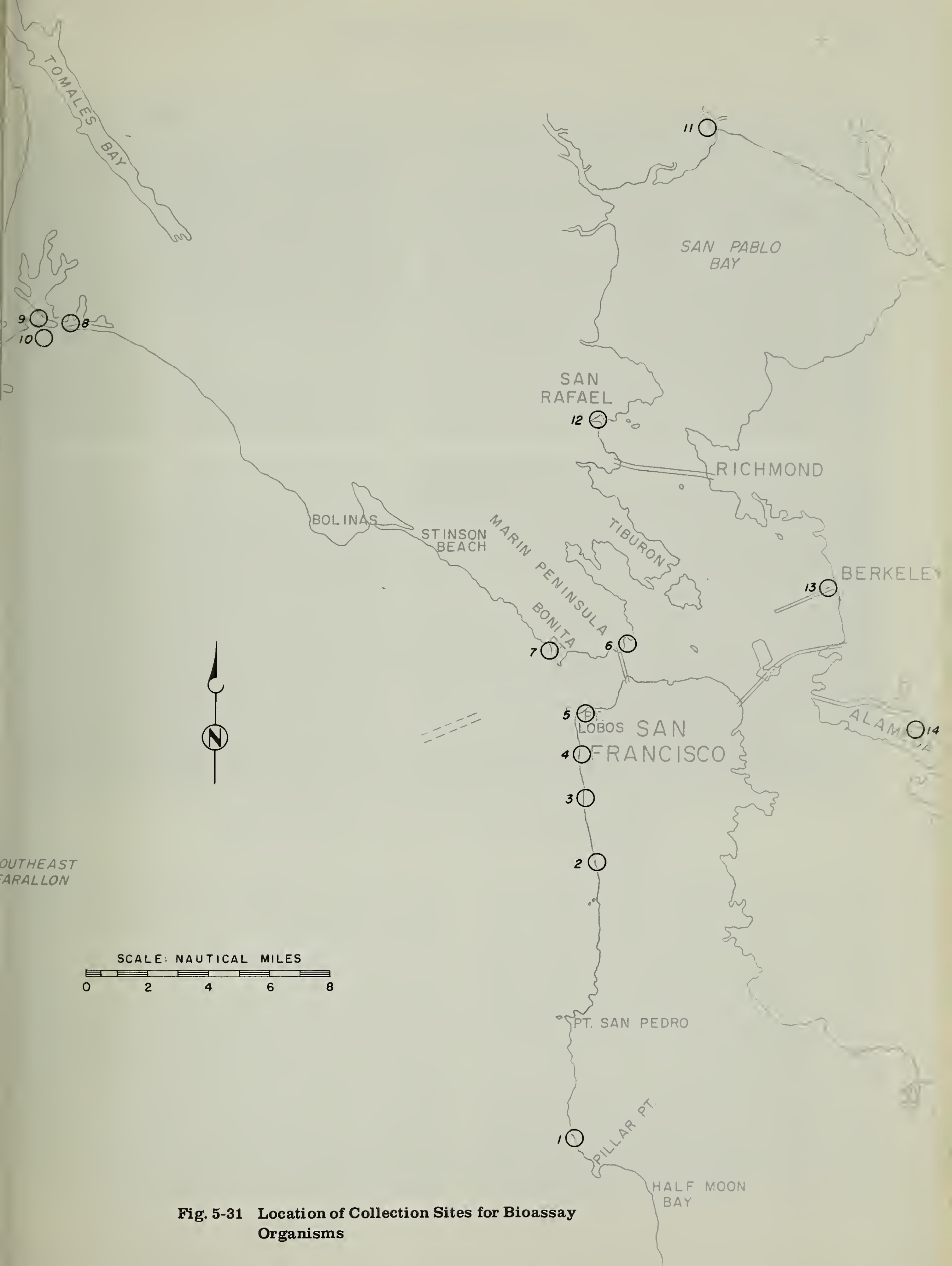


Fig. 5-31 Location of Collection Sites for Bioassay Organisms

The organisms used in laboratory studies were collected by a number of different methods, including beach seine, throw net, trapping and scuba diving.

surveys obtained a variety of clams and sea urchins. In intertidal areas such as rocky tidepools and mud or sand flats, specimens were hand collected by digging, box screening and small dip netting. Shore crabs, sand crabs, ghost shrimp and whelks were most frequently sampled by hand. Finally, various trapping procedures were used. Minnow traps collected pipefish in San Francisco Bay, and large commercial crab traps were used to collect gravid Dungeness crabs.

The collected specimens were transported immediately to the laboratory in 20-gallon tanks under aeration. At the laboratory the collections were sorted to species and put in large aerated constant-flow holding tanks for a minimum period of five days of acclimation. Temperatures were held constant at 12 deg C, ± 1 deg. During this period diseased, sluggish or parasitized fish were culled and discarded.

Feeding Requirements

The need for a supply of food for the test organisms was evident from the beginning of the laboratory research. First, it was often necessary to keep some organisms for long periods of time before bioassays could be conducted. This was common in rare species where insufficient numbers were available for immediate testing. Second, many of the bioassays were long-term (chronic) studies lasting several weeks. This was particularly true in the Dungeness crab growth experiments. Third, larval and juvenile organisms often had very high metabolic rates and hence required a constant supply of food for survival. Finally, it was important to separate effects due to toxicity from those due to starvation, cannibalism or competition in the actual experiments.

The many life stages and species studied in the laboratory made it necessary to obtain food from a variety of sources. It also became evident early in the investigations that most of the test organisms would eat only live food. Three sources supplied the majority of food utilized during the research program. The first and most widely used food organism was the brine shrimp, *Artemia salina* (Fig. 5-36). Eggs of *A. salina* were obtained from pet stores and cultured in shallow pans. The larvae, called nauplii, were collected after the eggs had hatched by attracting them to one end of the culture vessel by means of an incandescent light and pipetting them into food containers. *Artemia* nauplii was the main food source for all larvae used in the bioassay studies. Adult brine shrimp were also purchased in pet stores and used to feed fish and adult invertebrates.

The second source of food was natural plankton. A No. 20 mesh plankton net was attached to the inflow line of the submerged continuous flow pump. The net was backflushed daily into plankton containers and the large organisms removed. Aliquots of the plankton were equally divided among the experiments in progress and provided a nutrient supplement to the *Artemia* food. Natural plankton was supplied only to experiments using larger fish and invertebrates, because in bioassays with small organisms there was the possibility that the plankters might compete with or feed upon the test animals.

The third food source was fresh adult perch and other fish which were supplied to the various experiments studying shrimp and crabs. Fish were collected by beach seining in the vicinity of the laboratory or by purchase from fish markets. Some of the fish was frozen until used in the laboratory, but this observedly did not affect feeding by the crabs and shrimp.

During the research program no attempt was made to measure exactly the food organisms that were introduced into each experiment. Food ad-

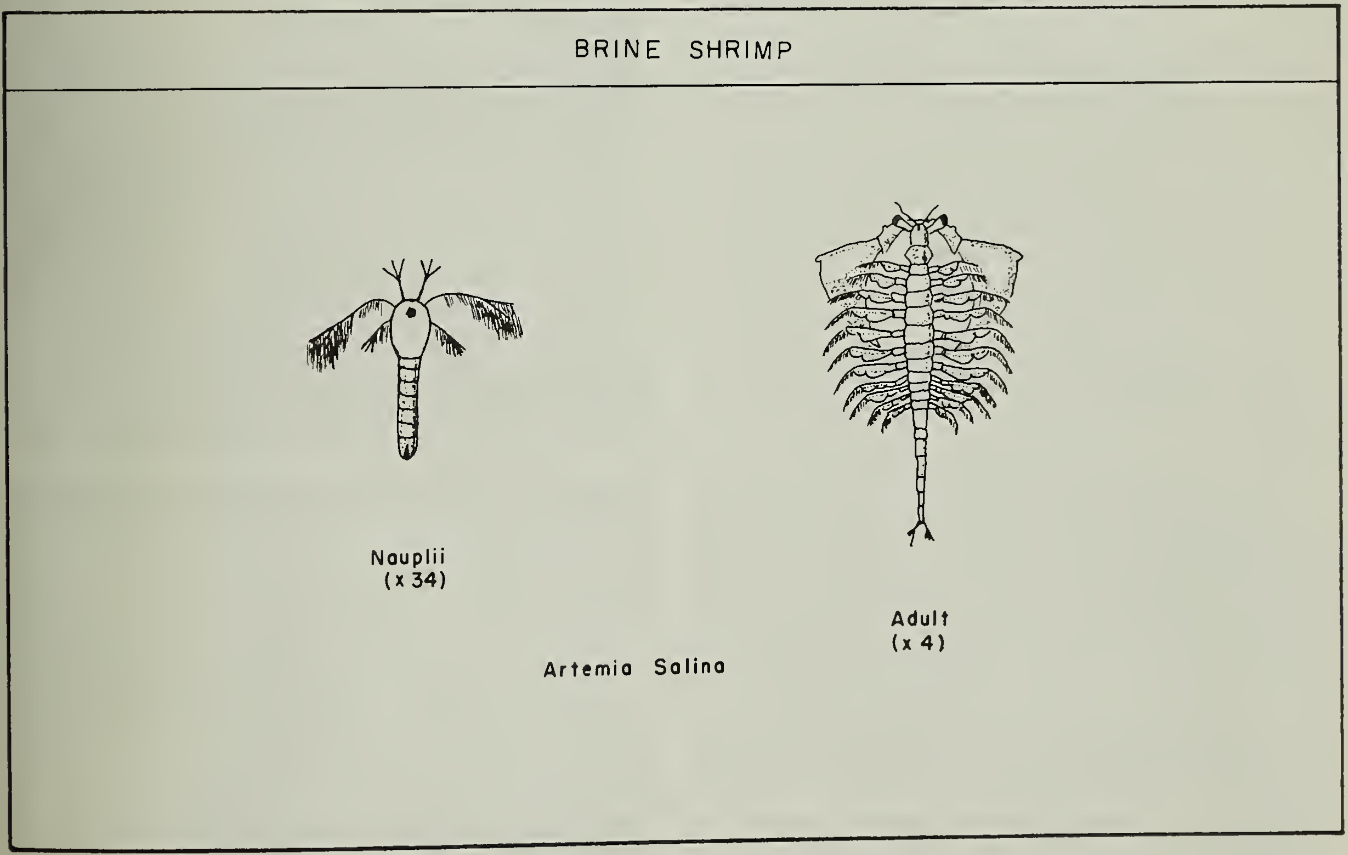


Fig. 5-32 Principal Food Organism

ditions were equally divided among the replicates of a bioassay, and the quantity fed was reduced if large amounts of food were left over from previous feedings. Also, an attempt was made to keep the availability of food within the limits of what might be found in the natural environment. Undoubtedly, some additional food was introduced with the dilution water, as generally no filtration was used except in continuous flow or larval experiments. Also, some food was probably introduced in the composite effluent. However, any effects that food additions produced during an experiment were equally found throughout the replicates or they were the result of the different dilutions of effluent tested. The effect of nutrient sources in the effluent composite was a factor which required study along with toxicity, if the complete effect of a waste discharge was to be predicted.

Static Bioassays

The static bioassay was used to test toxicity response of juvenile and adult fish and invertebrates to dilutions of composited San Francisco sewage effluent. These experiments were short term (96 hours) tests which measured acute toxicity by means of mortality. The bioassay procedure is particularly useful in quantifying highly toxic substances but is limited by lack of response in measurement of low or long-term toxicity. The procedures used in these tests were modeled after the method described in Standard Methods for the Examination of Water and Wastewater.[76] This test has been used extensively by a number of investigators and control agencies for routine toxicity measurements using the three-spined stickleback as a test organism. Some modifications of the method were necessary to accommodate the variety of fish and invertebrates to be studied.

Methods and Materials. The static bioassays were conducted in aged plastic containers. Three sizes of trays were used (7, 13 or 30 liter) depending upon the number or size of the organisms to be assayed. Before the start of the bioassay, each container was filled to a base level with fresh bay water and a volume of effluent sample was added to produce the desired dilution. The final volumes of test solution were approximately 5, 10 and 20 liters, respectively, for the three test containers.

In each experiment one or more control replicates was tested. The control contained no effluent and measured only the effect of the experimental procedures or background toxicity on the test organisms. A typical bioassay contained one control and five to six effluent dilutions. The range of effluent dilutions tested was from one part sewage in 200 parts background water (1:200) up to pure effluent (1:0). This range of dilution was often necessary to accurately measure the TLm (median tolerance limit) of the various organisms tested. The TLm measurement refers to that concentration of test substance which will result in 50 percent survival of the experimental organisms at the end of the test period, usually 96 hours. TLm corresponds to the median lethal dose, or LD_{50}, which is frequently used in toxicity studies

In those bioassays where high concentrations of municipal effluent were evaluated, the salinity of the test medium often fell below normal marine conditions. To compensate for possible salt effect, sodium chloride was often added to bring the salinity up to 26 ppt, equivalent to the average salinity of the background dilution water.

Static bioassays of juvenile and adult marine organisms were conducted to assess the effect of dilutions of San Francisco sewage effluent.

Once the proper dilutions had been prepared, the test fish or invertebrates were carefully transferred from the large holding containers to the bioassay trays. Usually ten individuals from each species were added to each replicate. This number was found to be the minimum required to achieve statistically significant results. In most experiments, only one species was added to the test solution. On occasion, however, two species were combined in the large tray experiments. These species were chosen to be specifically non-interacting. Where the experimental organisms were not of equal size, an attempt was made to place representatives from each size group in each tray. This gradation was required to reduce the physiological differences that might occur between different age and size individuals from the same species.

At the same time that the organisms were being added, pH and temperature measurements were made and aeration was begun. Aerators supplied a constant volume of air through air stones to each tray. The addition of air to the static bioassays served two purposes. First, the air was necessary to compensate for the increased oxygen demand brought about by large numbers of organisms in a relatively small space. Aeration divorced mortality due to decreased oxygen tension from the toxicity-related mortality. It was noted, however, that in most experiments with fewer organisms simple diffusion across the water surface provided sufficient oxygen.

The second beneficial effect of constant aeration was circulation throughout the containers, which kept the solution mixed and aided in the transport and dispersion of biologically created materials such as carbon dioxide. In some experiments the settling of suspended material would have been considerable without constant mixing.

The test bioassays were checked daily. The number of surviving organisms and the apparent condition of the survivors was noted. At each check all dead specimens were removed from the test containers to prevent contamination of the surviving organisms by bacteria or the products of decomposition. At the end of the second day a quantity of test effluent corresponding to approximately one-quarter of the initial dilution was added to each replicate. This addition was made to compensate for any possible reduced toxicity of the effluent mixture due to biological degradation. Food in the form of brine shrimp or natural plankton was usually added in equal aliquots to the test containers at each check.

Fish Bioassay Results. Of the many hundreds of fish obtained during the collection surveys, only seven species were collected in sufficient numbers to be used in experiments with statistically significant results. A minimum of ten fish per container was required and with six replicates per bioassay 60 fish were necessary for one experiment. This often meant that more than 100 fish of a single species had to be collected to allow for possible mortality through the catching, handling, transporting and acclimatizing processes. A minimum of three experiments were conducted on each species at each dilution.

Records for all experiments are presented in Volume 2, Data Supplement. The average percent survival for the studied species are reported in Table 5-12. This table is the composite of 24 experiments. When sufficient test organisms were available, bioassays were conducted which studied response in all eight concentrations of composite effluent. When large numbers of test organisms were not immediately available, bioassays were conducted with dilutions from 1:100 down to 1:5. Study was focused on these dilutions because they bracket the lowest range of effluent dilutions which might be found in the receiving waters.

Response in the shiner perch was relatively similar until dilutions less than 1:2 were reached. Differences between survivals in the control and high dilutions were possibly the result of variability in experiments and origin of test organisms. Percent survivals in walleye surfperch were also similar to the responses of shiner perch throughout the dilutions tested. Insufficient organisms were available for study in the low dilutions. In the walleye surfperch there did appear to be a slight increase in toxicity at the 1:5 dilution.

Adequate numbers of the mottled sanddab were available for bioassays in dilutions down to 1:1. Throughout the concentrations tested the mottled sanddab showed no significant effect of effluent toxicity. The average percent survival in all dilutions tested was 93.2. Juvenile lingcod were obtained in sufficient quantity for only one experiment with a control and two dilutions. In all of these replicates, however, survival was 100 percent at the end of 96 hours.

Sculpin were tested in both single and mixed species bioassays. Mixed bioassays usually included the addition of an invertebrate, such as turban snails or hermit crabs, to the test container. Sculpin survival was high (80 percent or greater) in all dilutions tested. There was no difference in

Table 5-12 Static Bioassays of Marine and Estuarine Fish

Organism	Average percent survival after 96 hours Dilution ratio, effluent: dilution water											
	Control (0)	1:100 (1)	1:50 (2)	1:20 (5)	1:10 (10)	1:5 (20)	1:2[s] (33)	1:2[p] (33)	1:1[s] (50)	1:1[p] (50)	1:0[s] (100)	1:0[p] (100)
Shiner perch Cymatogaster aggregata	90	100	71	93	78	75	20	265	0	0		
Walleye surf perch Hyperprosodon argenteum	94	100	100	83.3	83.3	66.6						
Mottled sand dab Citharichthys sordidus	100	100	100	95	85	90	100	100	86.5	75		
Ling cod Ophiodon elongatus	100	100	100									
Skulpin Scorpaena guttata	90	100	100	80	80	80						
Rock bass Sebastodes sp.	100	100	100	100	100	100	100	100	100	90	0	
Three-spined stickleback Gasterosteus aculeatus	86	85	90	100	100	100	80	96.6	60	75	2.5	46.6

Figures in parentheses are the percentage of sewage effluent.

[s] Salinity adjusted to the level of the diluting water by addition of NaCl.

[p] Salinity not adjusted.

percent survival between mixed and single species tests.

Rock bass were available in large numbers throughout most of the year. Consequently, this species was exposed to all concentrations of composite effluent. In all dilutions except pure effluent survival was 90 percent or greater. In 100 percent effluent none of the fish survived 96 hours. The high resistence of the rock bass to all but the lowest dilution was not unexpected. This species exhibits a high degree of adaptability by being distributed throughout a wide variety of habitats in San Francisco Bay and the Gulf of the Farallones. Many of these habitats are located in the vicinity of existing discharges.

Three-spined stickleback were also obtained in sufficient numbers for a complete bioassay investigation at all dilutions. This fish is normally found in the upper estuary and has been used extensively as a standard bioassay organism. Its incorporation in this study is primarily for comparison. The results of the bioassays demonstrated that there was a high survival rate in test fish until pure effluent composites were studied. Some small reduction in percent survival was indicated at the 1:2 and 1:1 dilutions. Stickleback survival pattern was found to resemble closely that found in the mottled sanddab.

The TLm and LD_{10} for the fish tested are presented in Table 5-13. The TLm is found from Table 5-12 by determining percent of effluent which resulted in 50 percent survival of the test organism. There was a significant difference in TLm for the organisms tested. The species with highest resistence (greatest tolerance) to sewage effluent was the three-spined stickleback, with a TLm of 90. Least tolerant of those measured was the walleye surfperch, with a TLm of 24. This emphasizes the importance of selecting organisms from the environment that is going to receive a waste discharge if the ecological impact of that discharge is to be evaluated.

As a practical matter, a 50 percent survival of all organisms would not be considered adequate environmental protection. If instead a 90 percent survival (LD_{10}) is arbitrarily chosen as a protection limit, a different tolerance picture is presented. Ten percent mortality would be accounted for by the susceptibility of the old, diseased or feeble individuals to any environmental change. The dilutions required to attain this survival are presented in the third column of Table 5-13. These dilutions often do not parallel the TLm because tolerance, as measured by percent survival, is not always linear with effluent concentration. For example, the effluent dilutions required

Table 5.13 TLm and LD-10 for Static Fish Bioassays

Organism	TL_m, percent	Estimated minimum dilution for 90 percent survival (LD 10)
Shiner perch Cymatogaster aggregata	27	1:10
Walleye surfperch Hyperprosodon argenteum	24[a]	1:15
Mottled sand dab Citharichthys sordidus	50	1:1
Ling cod Ophiodon elongatus	5[a]	b
Skulpin Scorpaena guttata	20[a]	1:20
Rock bass Sebastodes sp.	75	1:1
Three-spined stickleback Basterosteus aculeatus	90	1:2

[a] Estimated values from Table 5-12.

[b] Greater than 90 percent survival in all dilutions tested.

to produce 50 percent survival (TLm) and 90 percent survival might be quite similar in one species and yet quite different in another.

Of all the fish studied, the sculpin required the highest dilution (1:20) of municipal effluent to be assured of 90 percent survival over 96 hours. At the other extreme, the rock bass required only that the composite effluent be diluted 1:1 with background bay water for 90 percent survival. Walleye surfperch, with the lowest TLm, can be assured of 90 percent survival as long as dilution exceeds 1:5. The three-spined stickleback, with the highest TLm, required dilutions greater than 1:2.

Invertebrate Bioassay Results. The 96-hour static invertebrate bioassays encountered the same problem that accompanied the fish-bioassays. In many species it was not possible to collect sufficient organisms for statistically significant results. Of the 19 invertebrates collected, ten were obtained in adequate numbers for analysis. The same dilutions used in the fish bioassays were investigated for invertebrates to enable ready comparisons. Like the fish bioassays, low effluent dilutions also had salinity adjusted and salinity nonadjusted replicates. Also, when sufficient organisms for complete bioassays were not obtained, the higher dilutions were studied first. Finally, an attempt was made to run at least three experiments at each concentration. The average percent survival for the invertebrates studied is reported in Table 5-14. The results of each experiment can be found in Volume 2, Data Supplement.

Percent survival in two species of crabs studied, *Pagurus samueus*, the hermit crab, and *Hemigrapsus oregonensis*, the shore crab, were quite similar. Both species exhibited a high resistance to dilutions of San Francisco sewage effluent. It all dilutions tested survival was essentially 100 percent over 96 hours. In the sand crab, *Emerita analoga*, however, survival was distinctly affected by sewage effluent in dilutions below 1:20. The natural habitat of these different crabs may account for difference in their sensitivity. Both the hermit crab and the shore crab are rocky intertidal forms and are constantly being exposed to environmental change. The sandcrab, on the other hand, is a sandy beach species which avoids changes in its environment by burrowing beneath the sand. Resistance to change (tolerance) is built into the first two crabs where it is lacking in the third.

Three species of shrimp studied during the static bioassay research were the bay shrimp, *Crago* sp., the pink ghost shrimp, *Callianassa californicus*, and the broken-back shrimp, *Spirontocaris paludicola*. Adult organisms were assayed in the first two species and larval shrimp in the third species. Survival in the bay shrimp initially appeared different from survival in the other shrimps. In the bay shrimp percent survi-

Table 5-14 Static Bioassays of Marine and Estuarine Invertebrates

Organism	Average percent survival after 96 hours Dilution ratio, effluent: dilution water											
	Control (0)	1:100 (1)	1:50 (2)	1:20 (5)	1:10 (10)	1:5 (20)	1:2[s] (33)	1:2[p] (33)	1:1[s] (50)	1:1[p] (50)	1:0[s] (100)	1:0[p] (100)
Hermit crab Pagurus samuelis	100	100	100	100	100	100						
Shore crab Hemigrapsis oregonensis	99	99	100									
Sand crab Emerita analoga	82.5	78.5	61.5	73	36.5	-	0	0				
Bay shrimp Crago sp.	64	58	38	70	50	48	28	36	12	12	0	0
Pink ghost sprimp Callianassa californiensis	100	100	100									
Turban snail Tegula funebralis	100	100	100	100	100	100						
Sea urchin Stronglocentrotus purpuratus	100	100	100									
Bent-nosed clam Macoma nasuta	100	100	100	100	100	91	91	100	100	82		
Ribbed horse mussel Volsella demissus	100	100	100	100	100	100	100	100	100	100		
Broken-back shrimp Spirontocaris paludicola	100	90	90							70		0

Figures in parentheses are the percentage of sewage effluent.

[s] Salinity adjusted to the level of the diluting water by addition of NaCl.

[p] Salinity not adjusted.

val gradually diminished with increasing concentration until survival eventually collapsed at dilutions less than 1:1. This shrimp, however, was difficult to handle in the laboratory and high mortalities were often encountered in control replicates as well as dilution replicates. If dilution survivals were compared to control survival, it was observed that the bay shrimp behaved similar to the other shrimps. Both the pink ghost shrimp and the broken-back shrimp had high survivals (greater than 90 percent) in all dilutions except pure effluent. Unfortunately, the availability of test organisms limited the dilutions that could be studied in these shrimp.

Survival of the turban snail, *Tegula funebralis*, purple sea urchin, *Strongylocentrotus purpuratus*, and the horse mussel, *Volcella demissus*, was 100 percent in all dilutions tested. Specimens of the turban snail and horse mussel were available in large numbers and most dilutions were tested. Small purple sea urchins were not obtained during the later program and therefore only high dilutions were studied. These species are all intertidal forms and would normally be subject to large variations in their environment. This natural fluctuation, and the organism's adaptation to it, may account for their high tolerance.

The bent-nosed clam, *Macoma nasuta* was available for study throughout most of the laboratory program. All dilutions except pure effluent were eventually tested. Like most of the other invertebrates, the bent-nosed clam exhibited a high percent survival in all dilutions studied. Only at dilutions below 1:1 was a slight toxicity evident.

Calculations of TLm and LD_{10} for the invertebrates studied are presented in Table 5-15. For the most part values for TLm could not precisely be determined. Only in studies with the sand crab and bay shrimp were survivals reported that allowed for accurate TLm determination. In all other species tolerance was so high that 50 percent mortality was not encountered at any dilution. Of these two species, the bay shrimp (TLm about 33) was less sensitive to effluent dilution than the sand crab (TLm about 6).

Table 5-15 TLm and LD-10 for Static Invertebrate Bioassays

Organism	TL_m, percent	Estimated minimum dilution for 90 percent survival (LD-10)
Hermit crab Pagurus samuelis	$20^{a,b}$	c
Shore crab Hemigrapsis oregonensis	$2^{a,b}$	c
Sand crab Emerita analoga	6	$1:50^{b}$
Bay shrimp Crago sp.	33	$1:100^{b}$
Pink ghost shrimp Callianassa californiensis	$2^{a,b}$	c
Broken-back shrimp (larvae) Spirontocaris paludicola		1:100
Turban snail Tegula funebralis	$20^{a,b}$	c
Purple sea urchin Strongylocentrotus purpuratus	$2^{a,b}$	c
Bent-nose clam Macoma nasuta	$50^{a,b}$	$1:1^{b}$
Ribbed horse mussel Volcella demissa	$50^{a,b}$	c

[a] Estimated values from Table 5-14.

[b] Greater than listed value.

[c] Greater than 90 percent survival in all dilutions tested.

The determination of the dilution required to assure 90 percent survival was also imprecise in many species. In all but four species the test organisms had survivals greater than 90 percent. Of those species analyzed, the bay shrimp was most sensitive and required dilutions greater than 1:100 for 90 percent survival. This low tolerance was possibly a reflection of the general laboratory sensitivity of the species rather than solely an effluent response. At the other end, the bent-nosed clam required dilutions no greater than 1:1 for 90 percent survival.

Static Bioassay Summary. Composite San Francisco effluent was relatively non-toxic to all test species until dilutions less than 1:20 were studied. Furthermore, only in the sand crab and bay shrimp bioassays was survival as low as 50 percent measured in dilutions greater than 1:2. All studies indicated that a significant toxic effect from the composite effluent could not be demonstrated after 96 hours exposure in dilutions greater than 100 to 1.

Several limitations are inherent in the static bioassays. First, tests are only conducted for 96 hours and therefore reflect only acute toxicity. Second, the organisms tested reflect only those that were widely abundant. It is possible that more sensitive species were present in the environment but were not collected. Third, the ability of some species and not others to survive the stresses of collection, handling, transportation and acclimation to new conditions may have meant that only the hardier individuals were available for bioassays. These tests would then indicate that the effluent was less toxic than might be the case in an environmental exposure. Finally, the experimental procedure required that organisms be within specified size limits (approximately 1/2-inch to 6 inches) for easy analysis. This, then, would often neglect many of the smaller species or young individuals of the tested species. It is known that the young of a species are generally more susceptible to environmental change. Also, large fish and marine mammals could not be tested. To resolve some of the questions left unanswered by the 96-hour static bioassays, static bioassays were conducted in environmental chambers.

Environmental Chamber Experiments

Small scale tests were needed if all forms of the biota were to be studied. Since studies of small organisms (eggs, larvae, juveniles or small adults) were simply not manageable with the standard static bioassay techniques; toxicity tests of microorganisms were conducted in environmental chambers. These tests were designed to complement the 96-hour static bioassays commonly used to test fish and large invertebrates. The results of each environmental chamber experiment are included in Volume 2, Data Supplement.

The environmental chamber is an apparatus which provides a rigorously controlled climate in which small scale tests can be performed. If elements of climate, such as temperature, humidity, light and air circulation were not rigorously controlled, the microenvironment in each replicate of the miniature bioassays would vary greatly with small fluctuations in the labratory environment. The environmental chamber was used to insure that only effects due to effluent concentrations were measured.

The environmental chamber was used to house static microbioassays which tested the effect of composite San Francisco sewage effluent on the hatching of Dungeness crab eggs and on the survival of larval stages of Dungeness crab, sand crab, bay shrimp and broken-back shrimp. Only those larval organisms were available in sufficient numbers for study during the research program.

Bioassays on eggs, larvae, and other tiny marine organisms were conducted in the controlled climate of an environmental chamber.

Apparatus. The environmental control apparatus used in these bioassays was a hinged steel box incorporated into a movable platform. The box was insulated and had an inside volume of 36 cu ft. The device was equipped for temperature control with cooling coils that controlled the internal temperature at 51 deg F ±2.0 deg. Power-driven air circulation aided in producing a constant environment in all parts of the chamber. Two fluorescent lights provided illumination and were also used for moderate warming. During the research program a timer was connected to the lighting and produced a simulated day-night regime.

Egg Hatching Studies. The first experiments in the environmental chamber measured the effect of San Francisco sewage effluent on the hatching of Dungeness crab eggs. In these studies 500-ml jars were filled with dilutions of composite sewage effluent and background receiving water. Gentle aeration was supplied to each container to provide circulation and to assure sufficient oxygen. As most of these tests were conducted before the bay water pumping system was installed at the laboratory, the dilution water was obtained from the California Academy of Science Steinhart Aquarium. This water was representative of near shore ocean water and came from a sand filtered intake at Ocean Beach, San Francisco. Subsequent tests, together with long experience at Steinhart Aquarium, showed that this water was not measurably toxic to marine organisms.

In the egg hatching experiments only dilutions equal to or greater than 1:20 were studied. Higher concentrations of effluent in these small experiments caused the eggs to spoil, probably as a result of bacterial buildup or chemical and bio-

The female Dungeness crab shown above has an egg mass on its abdomen which provided eggs and larvae for bioassays.

logical decay. In any event the studied dilutions encompass the maximum concentrations likely to be encountered in the environment.

The crab eggs used in each test were removed from the parent in the later stages of development, and approximately 100 were placed in each test container. Hatching date was estimated through experience by looking at the larval eye development within the egg. Only viable eggs were studied, as determined by observing a heart beat in the late developed egg. Eggs, and later larvae, were transferred in a small water column by means of a wide-mouth pipette.

Each experiment was checked every 24 hours for egg hatching, viability and bacteria or fungus growth. The dilution water was changed every 48 hours. When the first hatching was observed, the remaining eggs were transferred to new background water that contained no effluent, provided that they had been exposed for a minimum of 96 hours. This procedure assured that all eggs received the same exposure time to the effluent dilutions. As more eggs hatched, all larvae were removed from the test containers to prevent any possible interaction with the eggs.

Egg Hatching Study Results. The results of a series of bioassays which evaluated egg hatching of Dungeness crab, *Cancer magister*, are presented in Fig. 5-33. In these experiments well-developed eggs removed from a crab collected near Newport, Oregon were exposed to a control and three dilutions of composite San Francisco sewage effluent for seven days. On the seventh day hatching was observed and the eggs were transferred to 100 percent bay water. Hatching continued until the ninth day. The experiment was concluded on the fourteenth day when no new larvae had been observed for five days. At this time microscopic examination of the remaining eggs showed them to be nonviable.

Hatching began on the same day in all dilutions tested. There was, however, an immediate difference in the success of hatching from the various dilutions. In both the control and 1:100 dilution over 85 percent of all the viable eggs ultimately hatched. The two higher concentrations of composite effluent never achieved hatchings over 45 percent. The ultimate 85 percent hatch in the control and the 93 percent hatch in the 1:100 dilution were not significantly different. Also the difference between the ultimate 36 percent hatch in the 1:50 and the 42 percent hatch in the 1:20 dilution was not significant. However, the hatching difference between the higher dilutions and

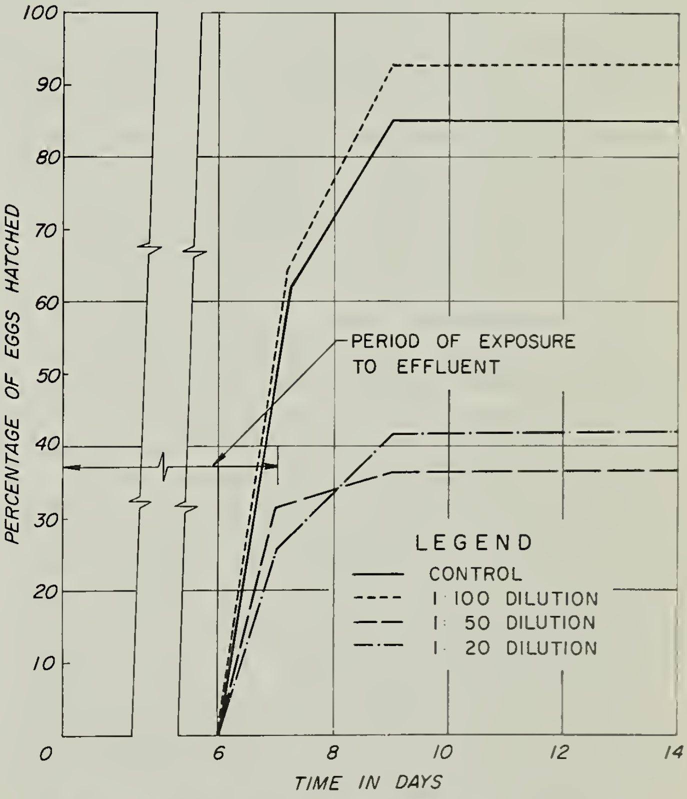


Fig. 5-33 Egg Hatching in Dungeness Crab in San Francisco Composite Sewage Effluent

the lower dilutions was significant. The percent hatches in the control and 1:100 were probably representative of viable egg hatch in the environment. The lower percentage hatches in the 1:50 and 1:20 effluent dilution appeared to be a direct result of the introduced effluent. The experiments also indicated that normal egg hatching occurs over a relatively short period of about two days.

Larval Bioassays. The second type of bioassay conducted in the environmental control chamber was concerned with the effect of sewage effluent on invertebrate larvae. In these tests Petri dishes (100 x 25 mm) were filled with 50 ml of various mixtures of San Francisco effluent and receiving water. The dilution water used during the early research was obtained at Steinhart Aquarium, but later San Francisco Bay water was substituted. No apparent difference in toxicity was measured between the two water sources. No aeration was provided to the larval experiments, as the large ratio of surface area to depth in the test dishes assured adequate diffusion of oxygen into the water.

Larvae were hatched from the eggs of adults that had no history of exposure to San Francisco effluent. Eggs were hatched in the laboratory in the background bay water and the larvae were added to the test dishes. During the numerous bioassays different numbers of larvae were introduced into the Petri dishes until it was established that approximately 25 was optimum for ease of handling and counting. Two or three duplications at each dilution were almost always tested to account for possible variations within the experi-

For the first 96 hours each experiment was checked every 12 hours. Viability, activity and general condition of the larvae were noted and the dead individuals were removed by pipette to prevent contamination of the living larvae. Larvae were observed and counted through a 90x dissecting microscope. Every 24 hours the entire water-effluent dilution series was replaced and food was added. Equal aliquots of brine shrimp nauplii provided the main food for the larvae. In some later experiments small aliquots of finely screened natural plankton were added as well.

During the environmental chamber studies a total of ten larval bioassays were conducted. These experiments ran from ten days to fifty days and tested larvae of Dungeness crab, sand crab, bay shrimp and broken-back shrimp. The Dungeness crab studies encompassed three larval stages.

Larval Bioassay Results. The Dungeness crab larvae studied in these bioassays came from laboratory-hatched eggs of crabs captured in Washington and British Columbia. Fig. 5-34 shows the results of experiments where newly hatched Dungeness crab larvae (zoea) were subjected to three dilutions of composite effluent. Zoea were transferred immediately upon hatching from bay water holding tanks into the dilutions of the experiment. Dungeness zoea were generally difficult to culture, and a moderate mortality was evident in all replicates. It was significant that at the end of 20 days there was no appreciable difference between survival in the control and in the lowest dilution. In fact, this pattern was generally observed between all replicates during the 25-day experiments. There never appeared to be a significant effect on mortality due to the presence of composite effluent. The 1:50 dilution initially had a slightly higher mortality, but survival percentage approached that of the other dilutions by the thirteenth day.

During the course of the experiments it was observed that the surviving zoea underwent two metamorphoses. Second stage zoea were produced on the fourteenth through the twentieth days and third stage zoea appeared on or about the thirtieth day.

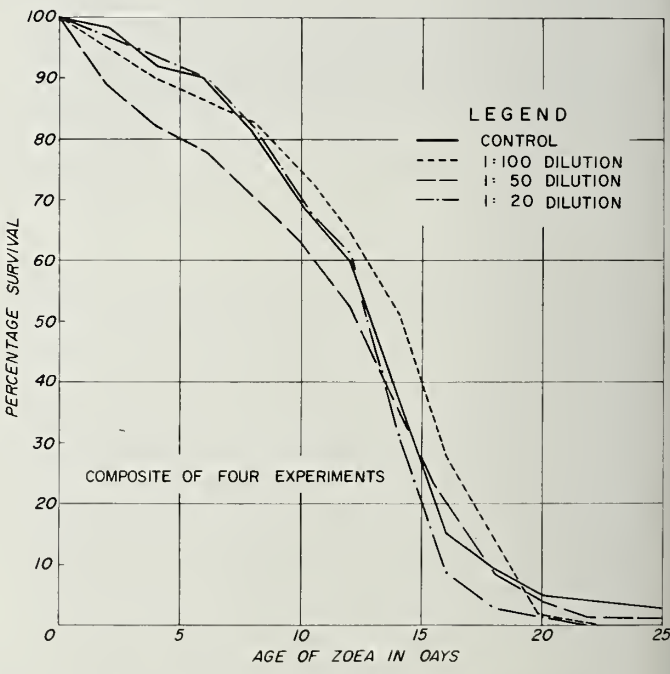


Fig. 5-34 **Survival of One Day Old Dungeness Zoea in San Francisco Composite Sewage Effluent**

Survival of 5-day-old Dungeness crab zoea in two dilutions of San Francisco effluent is presented in Fig. 5-35. The organisms used in these experiments were obtained from bay water control stocks of zoea five days after hatching. Because of the difficulty of culturing Dungeness zoea there were not sufficient numbers available to study more than the two dilutions presented. In the experiments there was a rapid mortality of zoea upon first introduction into the test environments. The high mortality observed was uniform throughout the three replicates tested and did not appear to be related to the presence of effluent. After the fourth experimental day, when the zoea were nine days old, the mortality rate was sharply reduced. From the ninth day to the twentieth day the mortality rate was similar to the rate observed in the early zoea studies (Fig. 5-34). By the 23rd day all zoea in the control and 1:50 replicates were dead. Low survival existed in the 1:100 dilution until the end of the experiment on the 30th day. The surviving zoea were observed to have undergone second stage metamorphosis by the 21st day.

Studies with 20-day-old zoea of Dungeness crab (Fig. 5-36) employed the same procedures as the 5-day-old zoea bioassays, except that the zoea were allowed to remain in the bay water control stock until the 20th day before transfer to the experimental dilutions. Larvae dieoff in the control stock left only enough advanced zoea for study in two effluent concentrations. Like the 5-day-old studies (Fig. 5-35), initial rapid mortality was observed in the 20-day-old experiments. After four days in the experimental dilutions the mortality rate declined. Early analysis of the zoea indicated that possibly they were beginning metamorphosis and hence were particularly susceptible to changes in the environment. During the metamorphosis process body resistance is low and all body functions are geared for rapid physiological and morphological change. Later analysis indicated, however, that a high initial mortality was common regardless of the age of the zoea and was likely related to a lack of resistance to the new experimental conditions.

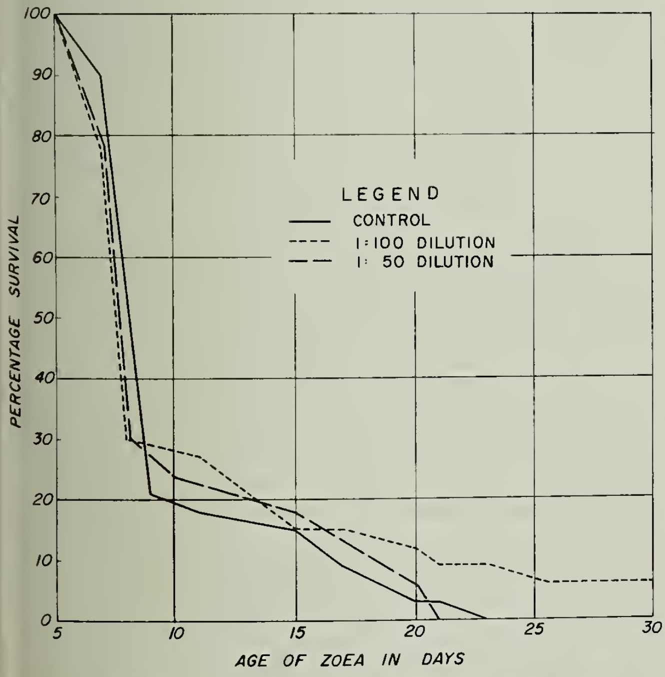


Fig. 5-35 Survival of Five Day Old Dungeness Zoea in San Francisco Composite Sewage Effluent

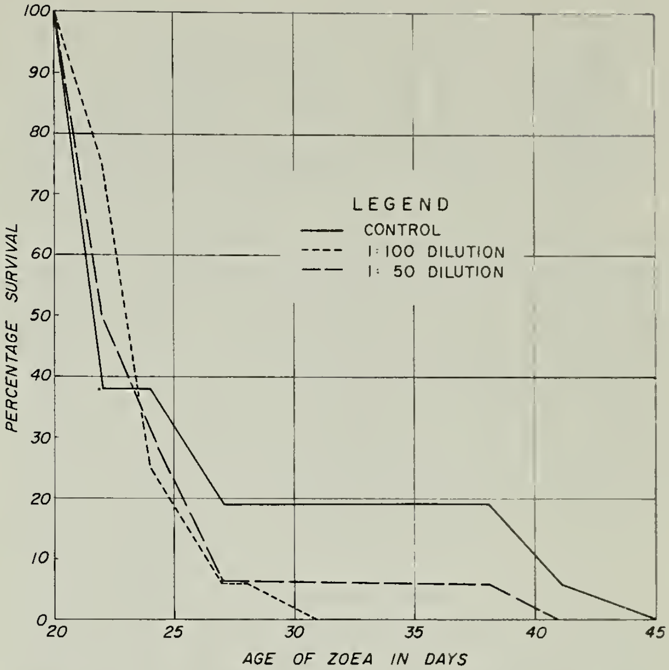


Fig. 5-36 Survival of Twenty Day Old Dungeness Zoea in San Francisco Composite Sewage Effluent

Eventual survival in the control replicate remained higher than survival in the two dilutions. All zoea died in the 1:100 dilution by the 31st day and all zoea died in the 1:50 dilution by the 41st day. Zoea in the control survived until the 45th day. The fact that survival in the 1:50 was better than the 1:100 dilution could not be accounted for except by differences in zoea viability through random sampling. There was some indication that dilutions of composite effluent had an effect on

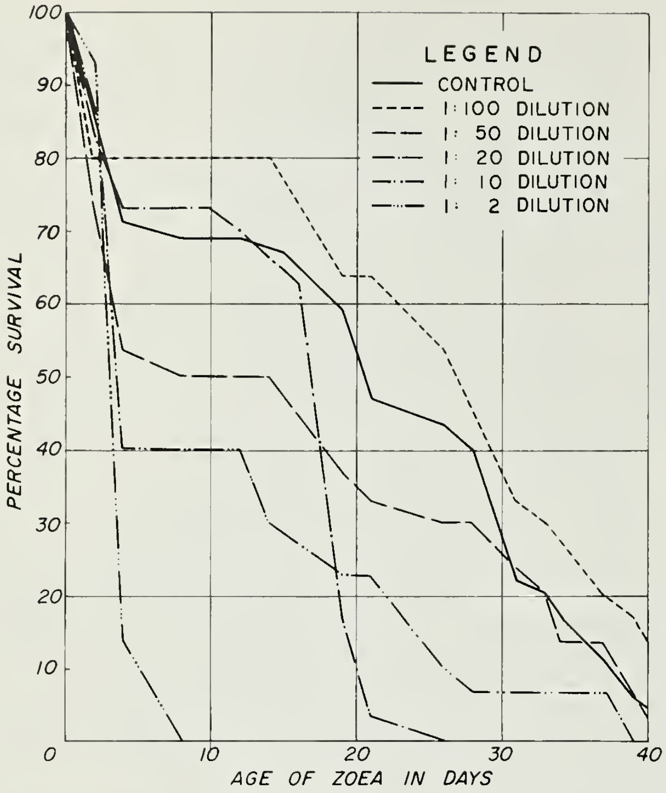


Fig. 5-37 **Survival of Sand Crab Zoea in San Francisco Composite Sewage Effluent**

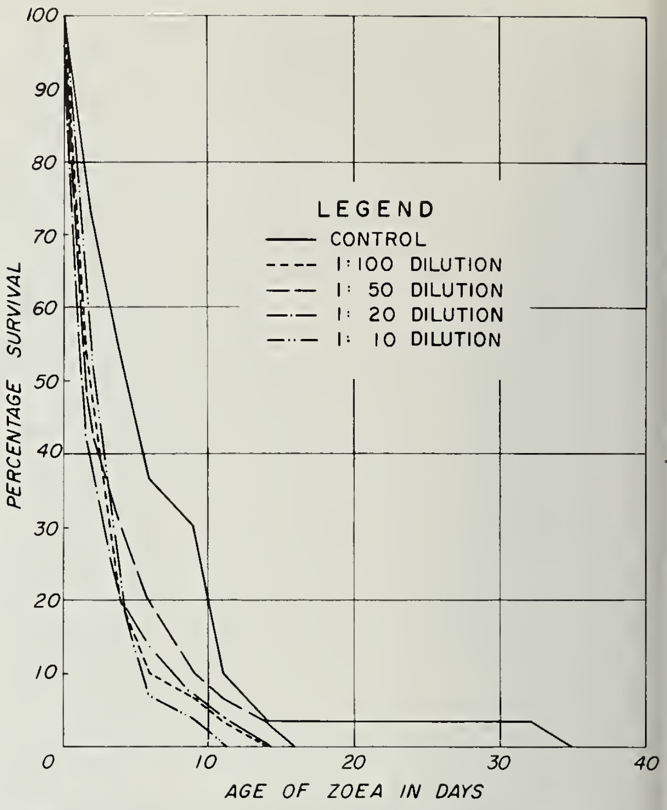


Fig. 5-38 **Survival of Bay Shrimp Zoea in San Francisco Composite Sewage Effluent**

20-day-old zoea survival, but the results were not conclusive.

The effect of composite effluent dilutions on zoea survival of the sand crab, *Emerita analoga*, is presented in Fig 5-37. Gravid sand crabs were collected from sandy beaches in Marin and San Mateo Counties and placed in the laboratory for hatching. Upon hatching, the zoea were placed in five dilutions of San Francisco sewage effluent. The results of these bioassays clearly showed a toxic effect of the effluent at very high concentrations. Survival during the first three days of the bioassays was approximately equal, but on the fourth day the low dilutions (1:2 and 1:10) exhibited significantly higher mortality rates. The 1:20 dilution initially had a low mortality rate but by the 16th day zoea began to die rapidly. The 1:50 dilution exhibited a high mortality which eventually recovered and surpassed the control survival by the 31st day. Both the control and the 1:100 dilution exhibited a moderate mortality rate throughout the experiment. However, from the third day to the end of the experiment 1:100 survival was significantly better than the control. This indicated that low dilutions of effluent benefited sand crab zoea survival, possibly because the effluent was providing a food source or micronutrient dietary supplement. The experiment indicated that this beneficial effect was equalled by a light toxic effect when the effluent dilution was about 1:50, and in lower dilutions the toxic effect overbalanced the beneficial effect.

The results of studies testing the survival of bay shrimp larvae (zoea) in four dilutions of composite effluent are presented in Fig. 5-38. These experiments were performed using the same procedures as in the previous experiments.

Bay shrimp zoea proved very difficult to culture in the laboratory and there was an initial high mortality in all tests. The control replicate possessed a slightly higher survival rate throughout the experiments. In all replicates except the control no zoea survived past the 16th day. A low percentage (4 percent) of zoea remained alive in the control replicate until the 35th day.

The results of the studies indicated a possible toxic effect of composite effluent. However, the fact that no significant survival differences were observed between the various dilutions, and that the control survival was only slightly better than the dilutions, indicated that more study was desirable.

A summary of the results from all first stage larval experiments in the environmental chamber at the end of 96 hours is presented in Table 5-16. The data show no significant difference in survival of Dungeness crab larvae between the control and the three dilutions of 1:100, 1:50 and 1:20. In the sand crab experiments survival fluctuated between the four replicates but did not appear to be a function of effluent dilution, since the 1:100 and 1:20 dilutions both had a higher survival rate than the control at 96 hours. Bay shrimp, however, did appear to be influenced by effluent toxicity. There was no significant difference between survivals at the three effluent concentrations, but all had higher mortalities than the control replicate.

A single 96-hour bioassay was also conducted with the broken-back shrimp, (*Spirontocaris paludicola*), in two effluent dilutions. In this test survivals were obtained in all replicates tested. There was a slight survival difference between the two dilutions and the control, but it was not statistically significant.

The relative difficulty of culturing the various larvae can also be observed in Table 5-16. Of the four organisms, the bay shrimp and sand crab larvae were sensitive to laboratory culturing procedures, and high mortalities resulted. These differences in laboratory survival emphasize the importance of control replicates in accurately assessing the influence of effluent dilutions on the test organisms.

Table 5-16 Static Bioassays of First Stage Invertebrate Larvae

Organism	Percent survival in various dilutions[a]			
	Control	1:100	1:50	1:20
Dungeness crab Cancer magister	92	90	82	94
Sand crab Emerita analoga	71	80	53.5	73
Bay shrimp Crago nigricauda	53.5	20	30	20
Broken-back shrimp Spirontocaris paludicola	100	90	90	b

[a] 96-hour static test in dilutions of San Francisco composite sewage effluent.

[b] No test.

Environmental Chamber Summary. The results of the Dungeness crab egg hatching bioassays indicated that there was a significant toxic effect of composite effluent at a dilution of 1:50. On the other hand, 1:100 not only exhibited no toxic effects but appeared to produce a slightly beneficial response.

The newly-hatched and 5-day-old Dungeness crab zoea bioassays suggested a stimulatory effect at dilutions greater than 1:50, but the results were not conclusive. More conclusive results were obtained from the sand crab larval experiments. In these studies the 1:50 dilution appeared to be the dilution at which stimulatory effects equalled toxic effects. In the 20-day-old Dungeness crab zoea and bay shrimp experiments, however, all concentrations of effluent produced detrimental effects on survival.

There are several possible explanations for the differences in survival between the tests. First, the 20-day-old Dungeness zoea and the bay shrimp zoea may in fact be more sensitive to effluent in any concentration. Second, late stage crab zoea and bay shrimp zoea are difficult to culture and small variations in the test environment may have influenced the results of these tests. Third, random sampling may have resulted in unequal distribution of viable larvae. Finally, as the tests of late stage zoea were limited by a shortage of organisms, the limited tests that were run may not have been representative of normal survival. The effect of effluent on late stage crab zoea and on other sensitive invertebrate larvae should be verified by additional tests, and the high mortality of crab zoea that apparently occurs during each molt, or metamorphosis, should also be more fully investigated.

Continuous Flow Bioassays

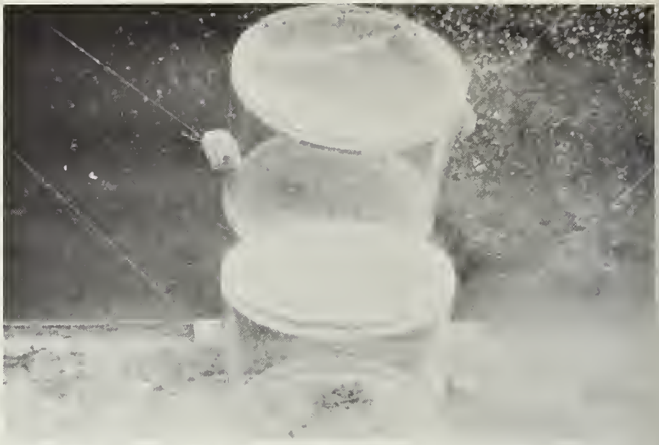
In continuous flow bioassay techniques new background water and dilutions of effluent are regularly supplied to the test organisms. This procedure has several advantages over static bioassay procedures. First, because the test organism is constantly in contact with a new supply of water, the system more accurately models the natural environment. Conclusions drawn in the laboratory are thus more likely to be accurate in predicting environmental effects. Second, the continuous flow system makes possible longer tests by preventing the buildup of substances produced by the test organisms themselves, such as waste products, which might be toxic.

Longer bioassays give information about chronic effects of the test medium which cannot be obtained from short term tests. Finally, problems such as oxygen depletion, bacterial growth and effluent degradation are reduced or prevented in continuous flow systems. On the other hand the continuous flow bioassay is more expensive to produce, requires a continuous supply of fresh background water and effluent, and is more difficult to operate and control. Continuous flow bioassays were conducted on Dungeness crab zoea and three-spined stickleback. The results are presented in Volume 2, Data Supplement.

Methods and Materials. The test containers for continuous flow bioassays consisted of four 30-gallon glass aquaria with inert silicon sealant joints. A 1-1/2-inch hole was sandblasted into the bottom of each aquarium for the placement of an adjustable polyvinyl chloride drainage standpipe. One aquarium was designated as the control and the remaining three were used for effluent dilutions.

Dilution water from the Horseshoe Bay water system was continually supplied to a 30-gallon reservoir through polyvinyl chloride pipes. The reservoir was used to provide a constant water pressure to each test aquarium. Immediately before entering the reservoir tank the water was passed through a packed spun glass filter to remove all plankton and detritus. The water was gravity fed from the reservoir to each aquarium, where the flow rate was regulated by means of an inert salt water valve.

Continuous flow bioassays were conducted in four 30-gal glass aquaria.



The glass chambers shown above contain Dungeness crab larvae and are suspended in a continuous flow bioassay aquarium.

Fresh effluent was provided to each of the three dilution aquaria by means of a continuously operating sigma-motor pump. The different effluent mix was introduced at the end of the aquarium opposite from the drainpipe. Dilution was regulated by controlling the ratio of flow between effluent and dilution water. The turn-over rate, defined as the length of time it would take to fill an aquarium, was controlled by adjusting the height of the drain pipe and regulating the total flow into the aquaria.

Both Dungeness crab zoea and three-spined stickleback were tested in continuous flow systems. When crab larvae were to be studied, pyrex glass chambers 2-1/2-inches in height and 3 inches in diameter were used as cages. Each end was covered by a removable netting of 62-micron mesh after the zoea were introduced. These chambers were suspended in the aquaria half way between the bottom and the surface. The zoea were fed by collecting brine shrimp nauplii in an eyedropper and introducing them into the cage through the netting. When three-spined stickleback were studied, they were simply introduced into the aquaria. Adult brine shrimp and natural plankton served as food for the fish.

Test organisms were observed and fed every 24 hours. Observations of crab zoea were made using a flashlight and magnifying glass. The

Dungeness crab zoea are positively phototropic and congregated in the flashlight beam. The number of viable zoea and their activity was observed through a magnifying glass and compared to initial records. Fish bioassays were monitored by counting the survivors and removing dead individuals with a dip net.

Continuous Flow Bioassay Results. Initial tests using the continuous flow system were 96-hour bioassays of first stage Dungeness crab zoea and three-spined stickleback in two concentrations of composite San Francisco sewage effluent. The results of these experiments are summarized in Table 5-17. In the first and second tests with crab zoea only one concentration of effluent was studied. The first test showed exactly the same survival in the 1:50 dilution as in the control at the end of 96 hours. In the second test a higher survival was found in the control than in the 1:50 dilution. In the third test two effluent dilutions were studied, and the 1:50 dilution had the highest survival of the replicates tested. The integrated results of the three tests indicated that there was no significant mortality effect due to composite effluent over 96 hours in dilutions equal to or greater than 1:50.

Table 5-17 Continuous Flow Bioassays

Organism	Test	Percent survival in various dilutions[a]		
		Control	1:100	1:50
Dungness crab First stage zoea	1	84.4	[b]	84.4
	2	90.0	[b]	70.8
	3	84.0	82.0	95.0
Three-spined stickelback	4	96.5	93.5	93.5

[a] 96-hour test in dilutions of San Francisco composite sewage effluent.

[b] No test.

The continuous flow bioassay with the three-spined stickleback also indicated no toxic effects, since all replicates produced essentially the same survivals at the end of four days.

A later experiment with the continuous flow bioassay system attempted to study long term effects of composite municipal effluent on first stage Dungeness crab zoea. The results of this experiment are presented in Fig. 5-39. Survival rates of the control and the two dilutions tested were moderate until the fourth day, when a large increase in mortality took place in both the dilutions and the control. After the sixth day the mortality rate dropped, but by this time few zoea were left in the experiment. The bioassay was discontinued on the eigth day when all zoea in the 1:50 dilution had died. Later examination of the zoea that had died during the fourth through sixth days showed that they were undergoing the first molt (metamorphorsis). Apparently the zoea are particularly vulnerable during this period in the natural environment. Similar mortalities associated with molting had been observed in the static tests. During the course of the experiment no significant difference in mortality rates was observed between the control and effluent dilutions.

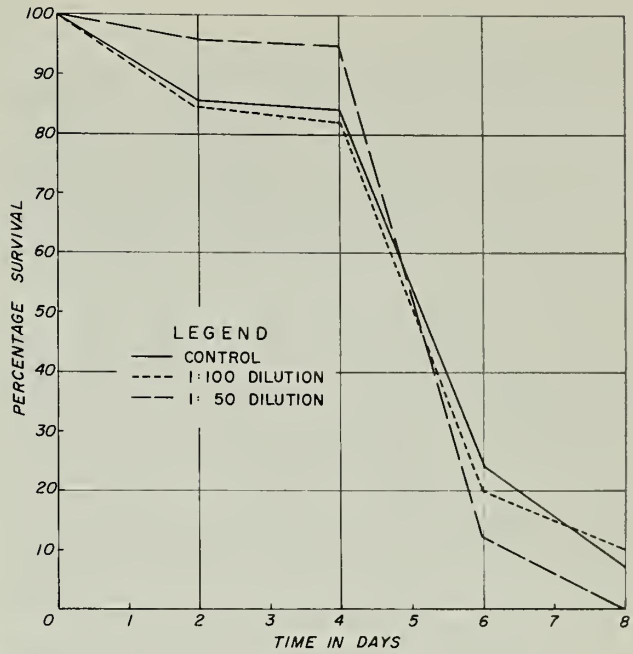


Fig. 5-39 Continuous Flow Bioassay of First Stage Dungeness Zoea

Continuous Flow Bioassay Summary. The results of all continuous flow bioassays indicated that there was no toxic effect from San Francisco composite sewage effluent in dilutions equal to or greater than 1:50. Unfortunately, the continuous flow apparatus was not perfected in the early part of the research program and only a limited number of experiments were run. By the time the system was operative very few Dungeness crab zoea were available for study. Further, the experiments that were conducted were too short to constitute a valid test of chronic effects.

Microcosm Studies

A microcosm is a miniature world which is designed to model an existing ecosystem. It, like the ecosystem, includes all component organisms together with the abiotic environment, forming an interacting system. When properly designed, the microcosm responds to changes like the larger ecosystem but can be more readily studied because of its size.

A long term microcosm experiment with Dungeness crab was conducted during 1970 to complement the rigorously controlled experiments being performed at the San Francisco Bay Marine Research Center. In this study all life stages of Dungeness crab were subjected to interactions with a model marine environment. Survival reflected the crabs response to predation, competition and other interactions as well as exposure to San Francisco sewage effluent.

The microcosm studies were performed by Dr. George Schumann of Marine Associates, San Diego, under an agreement with Brown and Caldwell. The research was carried out at the Marine Associates Laboratory, located at the San Diego Gas and Electric Company plant on South San Diego Bay, where it has access to continuous supplies of both bay water and heated bay water from the plant's cooling water discharge. The laboratory is well known for its research on the culture of larval marine organisms and its studies of the effects of warmed sea water on survival and growth of marine species. Under the agreement with Brown and Caldwell, Dr. Schumann grew Dungeness crab from larvae to adult form in three microcosms. Two of the microcosms contained dilutions of San Francisco composite sewage effluent, and the third served as a control. A complete report of the results of the investigation conducted by Marine Associates is included in Volume 2, Data Supplement.

Methods and Materials. At the Marine Associates Laboratory three 1000-gallon aquaria, each 4-ft x 8-ft x 4-ft, were filled with 900 gallons of sea water and allowed to stand for seven days. The three aquaria were salinity adjusted to 32 ppt by the addition of fresh water or composite effluent which had been air freighted from San Francisco in sealed, insulated carboys and refrigerated at 35 deg. F. One aquarium was established as the control, and no effluent was added. The other two aquaria received measured amounts of effluent to produce dilutions of 1:200 and 1:100. During the experiment small amounts of fresh water were continuously added to maintain the initial salinity and to replace water lost through evaporation. Temperature in the aquaria was maintained at 65 deg F, ±2 deg.

Two gravid Dungeness crabs that had been captured in Oregon were air freighted to the Marine Associates Laboratory where they were placed in shallow water tables. Upon hatching, the zoea were divided into three equal aliquots and added to the three acquaria. As hatching occurred over seven days, zoea were added nightly to each aquarium during the first week of the study.

Food was provided daily to each aquarium. Estuarine plankton and brine shrimp provided the main food sources. Plankton was collected daily by towing a 1-m plankton net (80 micron mesh) in San Diego Bay. Equal amounts of the fresh plankton were added to each aquarium. Brine shrimp larvae and adults were also collected daily from nearby salt evaporation ponds and added in equal aliquots to each acquarium.

Microcosm Results. In the microcosm experiment conducted by Marine Associates Dungeness crab were raised from newly hatched zoea to the adult form in each replicate. This development period took 74 days, which was faster than the 111 days reported in the literature.[60] It is believed that the warmer water of the microcosms speeded up larval development. This experiment was one of the few times that Dungeness crab have been reared to adult form entirely within the laboratory.

Dr. Schumann observed that the survival of Dungeness crab larvae varied significantly in the three test aquaria. He found low survivals in the control replicate and proportionately higher survivals in the two dilutions. He also observed that the resulting number of young *C. magister* crabs in the effluent replicates was greater than in the control replicate. He concluded that the higher survival rate in the two aquaria containing sewage effluent was probably the result of the proliferation of food organisms due to the addition of micronutrients in the effluent. Dr. Schumann's observations also led him to conclude that "the sewage effluent employed did not contain harmful or lethal substances exerting an immediate or long term detrimental effect on crab larvae."

In the test microcosms other organisms were inadvertently exposed to possible effluent effects. These included top smelt, gobys, harpacticoid copepods, barnacles, shrimp, mussels, crabs, tunicates, annelids, isopods and bryozoans. No detrimental effect on long term survival of these organisms was observed. In fact, since all of these organisms except the adult copepods entered the aquaria in the larval stage it was assumed that sewage concentrations of 1:100 or less were not detrimental to their development from larval to adult forms.

In a separate test using a similar microcosm technique, larvae of the American lobster, *Homarus americanus*, were exposed to a 1:100 dilution of San Francisco sewage effluent. The results of culturing lobster larvae in the diluted effluent and in natural bay water were virtually identical.

Stickleback Blood Study

An experimental study of the effects of composite San Francisco sewage effluent on blood composition of the three-spined stickleback, *Gasterosteus aculeatus* was conducted under the direction of Dr. Curtis Newcombe at San Francisco State College during 1970 by Mrs. Gretchen Kaplan. This research was used in partial fulfillment of the requirements for a Master of Science degree in the Department of Ecology and Systematic Biology. A summary of Mrs. Kaplan's work is included in Volume 2, Data Supplement.

Using adapted mammalian procedures, the hematological response of the three-spined stickleback to various concentrations of sewage effluent was investigated over a seven day exposure period. After first establishing the normal hematological picture of the organism, Mrs. Kaplan found that certain blood cells responded in number and form to high concentrations of composite sewage effluent.

Numbers of white blood cells (leucocytes) and thrombocytes changed in response to increased effluent concentrations. Thrombocytes function principally in the clotting of blood. The leucocytes were found to increase in dilutions less than 1:6. Progressively greater concentrations resulted in progressively greater counts. There was no significant increase in the 1:10 dilution tested. Thrombocyte numbers were also observed to increase when the test fish were put in dilutions of effluent less than 1:10. At the 1:10 dilution, however, there was a significant decrease in numbers of thrombocytes in the peripheral blood. As no higher dilutions of effluent were tested, the exact threshhold concentration of thrombocyte response was not determined.

Later analysis of the daily increase in both the leucocyte and thrombocyte numbers showed them to be directly correlated with bacteria levels in the effluent dilutions. The highest statistical correlation was found to exist between bacteria counts in the effluent and blood cell counts 48 hours later. This was interpreted to be a response of the organism to prevent possible bacteria invasion. A similar explanation for increases in leucocytes has been documented in mammals. Thrombocytes, however, possess no known bacterial defense function and their increase could not be accounted for by such an explanation.

Although red blood cells (erythrocytes) increased slightly in concentrations of effluent greater than ten percent, later analysis revealed that the increases were not statistically significant. Erythrocytes function mainly in the transportation of oxygen throughout the body. The hematocrit, or relative value of corpuscles and fluid in the blood, did not change with effluent concentrations.

The results of the blood investigations indicated that concentrations of composite San Francisco sewage effluent greater than 1:10 exerted a stress on sticklebacks by changing their blood composition. It may be assumed that a similar response would occur in some other fish species. In the stickleback initial response appeared to be a reaction of protection against large numbers of bacteria. This emphasizes the possible importance of reducing bacterial numbers in effluent discharge for the protection of marine animals.

Additional research in this field would be interesting, particularly studies with higher dilutions of effluent that would be more representative of concentrations in the marine environment. Also, the threshhold concentration at which blood cells are affected and the effect of long term exposure should be investigated.

The demonstration of an apparent stress response to bacteria in sewage by some fishes raises an interesting point. Other observers have reported that chlorination to reduce bacterial populations creates a stress on marine organisms. It would be of great interest to determine whether the bacteria or the bacterial control measures exert the greater stress.

Biostimulation Study

The biostimulatory effect of sewage effluent in the aquatic environment has been well documented. Biostimulation as used herein is defined as the enhancement of the growth of phytoplankton and other aquatic plant life. Depending on the characteristics of the receiving water, the controlling factor in biostimulatory response may be nitrates, phosphates or micronutrients such as thiamine and Vitamin B-12. All of these factors are present in domestic sewage effluent. One experiment was run at the San Francisco Bay Marine Research Center in an attempt to determine the threshhold level of biostimulatory response to San Francisco composite sewage effluent in sea water.

Five gallons of surface sea water was collected from a point four miles north of the Farallon Islands on September 2, 1970. The sample, which was assumed to represent background ocean conditions, was transported to the laboratory in inert insulated carboys. Initial chlorophyll a concentrations were measured from duplicate 100-ml samples extracted in 5 ml of 80 percent acetone and analyzed at 665 millimicrons on a Bausch and Lomb Spectronic 20 colorimeter. The sample was then divided into eight aliquots of 500 ml and added to Erlenmeyer flasks. Controls, 1:100, 1:50 and 1:20 dilutions were prepared using composite San Francisco sewage effluent. Four replicates with two duplicates at each concentration were tested. All flasks were placed in a shaker with gentle agitation. Continuous lighting was provided by fluorescent lights and temperature was held constant at 65 deg F. At the end of four days chlorophyll a measurements were made on each flask using the same procedures employed in the initial measurements.

The results of all chlorophyll a measurements showed no difference between the controls and the dilutions tested. Further, there was no significant change in chlorophyll concentration during the test period. The total chlorophyll levels during the test were very low, and apparently little phytoplankton was present in the sea water sample.

While the experiment was too limited in scope to support any general conclusions, the fact remains that the work did not document any biostimulatory effect of San Francisco sewage effluent even in dilutions as low as 1:20. Additional studies are needed in this area covering different locations and seasons of the year. For example when upwelling has enriched the surface ocean waters, the quantity of effluent required to produce a detectable change in phytoplankton levels may be different from that at the time the test was run.

SUMMARY OF RESULTS

The ecological program of the marine study for the City and County of San Francisco had two principal objectives: (1) to gather information on existing conditions in areas of the marine environment that might be influenced by a future submarine outfall, and (2) to predict the ecological effect of disposing of large quantities of treated municipal sewage effluent to the waters surrounding the City of San Francisco. To achieve these objectives the ecological program was divided into three sections: (1) a review of all literature relating to the resources of the San Francisco Estuary; (2) a field investigation of the marine environment which included a study of the seasonal changes in the benthos, nekton, plankton and intertidal biota; and (3) a laboratory investigation of the response of marine and estuarine organisms to dilutions of primary treated effluent from the City and County of San Francisco. Each of these sections included a detailed study of the Dungeness crab (*Cancer magister*) and a general survey of the total marine community. The results of each section of the ecological program are summarized below.

San Francisco Resources

1. Numerous investigations have dealt with the biota of San Francisco Bay, but literature relating to the flora and fauna of the nearshore Gulf of the Farallones is very limited.
2. Phytoplankton and zooplankton fluctuations within the San Francisco estuary appear to be seasonal. Zooplankton diversity was found to be typically less than phytoplankton diversity.
3. Productivity measurements made at two stations indicated that the high turbidity of San Francisco Bay water is the main factor in limiting algal growth. Nearshore stations outside of the Golden Gate fresh water plume had higher productivities than similar stations within the influence of the plume.
4. Laboratory studies with diatoms indicated that no large biostimulatory response would be expected upon the addition of an activated sludge effluent to San Francisco Bay water.
5. Benthic diversity changes seasonally very little in most areas of the San Francisco estuary. Only in those areas where large movements of the bottom occur could statistically significant changes in the biota be observed. The most common large benthic organism in the San Francisco estuary was the clam, *Gemma gemma*.
6. Benthos in the Gulf of the Farralones adjacent to San Francisco is very limited due to the very unstable bottom of shifting sand.
7. The salmon fishery is the most important commercial fin fishery in the San Francisco area. The salmon catch frequently exceeds two million pounds. Most fishing effort occurs along the migratory routes of the salmon in the northeast Gulf of the Farallones.

8. The pelagic group fishery, which includes albacore, herring and anchovy, has been declining in the San Francisco area over the past ten years mainly as a result of large drops in the herring and anchovy catches.

9. The stable group fishery, which includes salmon, also produces large catches of rockfish, English and Dover sole. Total catches from the stable group fishery have remained within normal ranges over the past 10 years and have not declined as has the pelagic group fishery.

10. Fluctuations in the total fin fish catch from the San Francisco area parallel fluctuations in the total commercial fish catch for the state of California; however, a decline in the total fish catch of the San Francisco area is more pronounced than in the state totals

11. Sport fishing effort in the San Francisco area is primarily related to party boat and shore fishing for salmon, striped bass and rockfish.

12. The value for wildlife habitats of the intertidal land surrounding the City of San Francisco is relatively limited. Most of the area is sandy beach, fill areas or piers.

13. Adult Dungeness crab have been reported from almost all areas of the San Francisco estuary, but the present distribution is mainly concentrated in central portions of San Francisco Bay and throughout the Gulf of the Farallones.

14. Dungeness crab mates from February to June. Sperm is stored within the female several months while the eggs mature. Fertilized eggs are carried on the abdomen of the female until hatched. Hatching generally occurs in January and February in the San Francisco area.

15. The normal development of Dungeness crab includes six larval stages, consisting of five zoea and a megalops. Total development at 51 deg F. from egg to adult form is 111 days. Temperature and salinity can influence larval development. Larvae captured in plankton tows were larger and slightly different in form than laboratory reared specimens.

16. The first stage zoea are the most difficult to raise in the laboratory and consequently are probably the most sensitive to environmental stress.

17. Nine species of *Cancer* occur on the West Coast. Four of these species are taken commercially in California, but *C. magister* constitutes more than 99 percent of the total crab catch.

18. The major fishing grounds for the San Francisco crab industry are in the western Gulf of the Farallones at depths between 20 and 40 fathoms.

19. Fluctuations in crab catch for the San Francisco area typically coincide with fluctuations in the crab harvest from all other locations. Major changes in oceanic conditions are thought to result in fluctuations in the crab populations.

20. The crab fishery of the San Francisco area has experienced a major decline since the 1956-7 season. Other localities experienced similar declines up to 1964 but have recovered in the past few years. San Francisco area crab fishery has remained at a fraction of previous levels.

21. Numerous factors have been studied to determine the result of the sustained low crab catches in the San Francisco area. The fact that the San Francisco crab fishery is on the southern limit of the commercially important distribution indicates that environmental conditions in this area may not be favorable for repopulation. Repopulation of Dungeness crab in the Gulf of the Farallones is also likely dependent upon larvae from southern communities being carried into the San Francisco area.

22. Relatively high concentrations of pesticides have been recorded in larval *C. magister* from the Gulf of the Farallones and Drakes Bay. These concentrations may be a major factor in the sustained low population levels of the market crab in the San Francisco area.

23. The fact that the Gulf of the Farallones previously supported larger populations of *C. magister* emphasizes the need to maintain a marine environment which will protect existing crab populations and permit future increases.

Field Investigations

1. Field studies were conducted from December 1969 through December 1970 in five phases; namely, plankton studies, benthic studies, diving studies, intertidal studies and in-situ cage studies.

2. The plankton sampling and identification program was conducted jointly with the California Department of Fish and Game.

3. From 85 plankton samples analyzed only three *C. magister* zoea were identified. It was impossible to determine if inadequacies in the sampling program or simply a lack of zoea in the plankton community resulted in the low number of identified *C. magister* zoea.

4. Frequent fluctuations in plankton numbers and diversities occurred during the sampling program. In many instances these fluctuations could be loosely correlated to changes in the physical environment. Ocean upwelling and fresh water runoff were the major factors affecting the plankton population at all stations.

5. During much of the year copepods were dominant at all plankton stations. When delta outflow was high, nonmotile plankters became scarce and species diversity was reduced. During this period the nonmotile plankters were unable to stay afloat due to the low water density caused by reduced salinity.

6. The benthos study phase of the field investigations analyzed samples taken by the Hydraulic Engineering Laboratory of the University of California at Berkeley as well as collections obtained by Brown and Caldwell.

7. On the basis of dominant taxa, diversity, productivity, substrate and location four distinct benthic communities were identified. The extent of each community was mainly controlled by bottom sediment type and wave action. The Near Reef community had the highest diversity and productivity; the Shelf community had the lowest diversity and productivity. The Bar community was characterized by changing patterns of wave action, currents, predominant taxa and productivity. The Bay community had low diversity and was characterized by high mud and silt fractions.

8. Few important economic species were identified in the benthic samples. The distribution of juvenile *Cancer* was reported from shell remnants. Almost all *Cancer* crabs came from Near Reef and Bar communities, but even in these communities the number of identified crabs was small.

9. Diving studies were performed by biologists at Lands End, Point Bonita, Muir Beach and Piers 33 and 35 in San Francisco Bay. Information was gathered to measure the effect of existing effluent fields on the marine environment and to obtain background data for future studies or monitoring programs.

10. Muir Beach, which was the most oceanic of the diving stations, had the greatest number of plants and animals. Point Bonita had 80 percent of the Muir Beach totals, Lands End about 60 percent and Piers 33 and 35 about 15 percent. The difference in substrate types and fresh water influence were the major factors that influenced the biota at all stations. All three ocean stations displayed a well-developed faunal composition but the flora was somewhat deficient, probably as a result of water turbidities.

11. The effect of the Richmond-Sunset outfall at Lands End was very localized and resulted in little or no reduction of subtidal species diversity. At Piers 33 and 35 the benthos was affected by the North Point effluent field within 50 feet of the outfall. At both locations, Lands End and Piers 33-35, however, subtidal species depression was restricted to a small area and it was often difficult to separate effluent effects from other environmental factors such as sedimentation, wave exposure, fresh water effects and substrate influences.

12. Seven intertidal areas were investigated during 1970. The Gashouse Cove, Lands End and Point Bonita stations were influenced to a large degree by fresh water outflow from San Francisco Bay. The Duxbury Reef, Rocky Point, Rockaway Beach and Moss Beach stations were mainly oceanic in composition.

13. Duxbury Reef and Moss Beach contained the highest diversity of plants and animals and were the most productive of all intertidal stations studied. The Point Bonita, Rocky Point and Rockaway Beach locations were considerably more restricted in size and habitat type and consequently had a lower species diversity. Gashouse Cove supported fewer animals and plants than all other areas, but this was undoubtedly a result of the limited substrate types.

14. Lands End was the only locality where the effect of a sewage field was observed. Within 50 feet of the outfall the intertidal zone was devoid of macroscopic algae. From 50 to 400 feet from the outfall the intertidal biota was noticeably reduced. Progressively father away the intertidal zone returned to normal diversity and luxuriance. Normal levels of plants and animals at Lands End were strikingly small, mainly as a result of the extreme weathering that the area encounters.

15. Cage experiments were conducted in the North Point effluent field to assess the toxicity of an existing discharge in San Francisco Bay and to complement laboratory toxicity studies. Test results indicated that there was no significant toxicity to three-spined stickleback associated with the effluent field from the North Point outfall. There was some evidence that bay water along the San Francisco shoreline was slightly more toxic than water on the north side of the bay. The source of this apparent toxicity was not identified.

Laboratory Investigations

1. Laboratory studies of toxicity and biostimulation in marine organisms were conducted at the San Francisco Marine Research Center on Horseshoe Bay from February through September, 1970.

2. All experiments were designed to model actual conditions found in the marine environment surrounding San Francisco. The apparatus used in experimentation was designed to re-

produce conditions actually found during field cruises. Static and continuous flow tests were employed.

3. The effluent studied during the laboratory program came from the City of San Francisco's three treatment plants. Effluent was composited in proportion to each plant's daily flow and used fresh in the various experiments. The dilution water used in all experiments came from San Francisco Bay or the Gulf of the Farallones. Actual dilutions of effluent and water used in the laboratory were based on oceanographic cruise data and engineering feasibility studies.

4. In the course of the laboratory investigations many hundreds of organisms were exposed to various dilutions of San Francisco municipal effluent. All of these organisms were collected from marine or estuarine environments in the San Francisco area. Tests included both short and long term studies on many life stages of fish and invertebrates. In addition, algae were studied in biostimulation experiments.

5. Static bioassays were used to study toxicity response in juvenile and adult fish and invertebrates. Short term (96 hours) tests were run, and toxicity was measured by means of mortality counts.

6. Seven species of fish were collected in sufficient numbers to obtain statistically significant results when assayed in dilutions of San Francisco effluent. Dilutions from 1:200 (effluent: water) to pure effluent were studied in static bioassays.

7. Shiner perch exhibited little toxicity response until dilutions less than 1:2 were studied. At this dilution significant mortality occurred. Walleye perch response to municipal effluent was similar to shiner perch.

8. Mottled sanddabs showed no toxicity effects at dilutions down to 1:1. Insufficient organisms were available for tests at higher concentrations. Juvenile lingcod were obtained in sufficient quantity for only one experiment at two high dilutions (1:200 and 1:100). No mortality was observed in any replicate.

9. Sculpin were tested in both single and mixed bioassays, involving the addition of another organism to the test container. Sculpin survival was high throughout all dilutions studied and there was no difference in percent survival between mixed and single species tests. No effluent effects were observed throughout the dilutions studied.

10. Rock bass exhibited no acute toxicity response to effluent dilutions until pure effluent was used as the test media. At 100 percent effluent none of the test fish survived 96 hours.

11. Three-spined stickleback were studied mainly for purposes of comparison with other effluent studies. Three-spined stickleback are not normally found in the marine environment surrounding San Francisco. The stickleback survival pattern closely resembled survival of mottled sanddab in response to municipal effluent. No significant effluent effects were observed until dilutions less than 1:2 were studied.

12. Of all fish studied the species with the highest resistance, as measured by its median tolerance limit (TLm), was the three-spined stickleback. The lowest TLm was recorded for the walleye surfperch.

13. The lethal dose that caused 10 percent mortality (90 percent survival) was also calculated. Of all th fish studied the sculpin required the highest dilution (1:20) of municipal effluent to be assured of 90 percent survival. At the other extreme the rock bass required only that composite effluent be diluted 1:1 with bay water to insure 90 percent survival.

14. Ten invertebrates were collected in sufficient numbers for statistically significant bioassay results. Low effluent dilutions were salinity adjusted in order to reduce the possibility of fresh water toxicity on marine organisms.

15. Three crabs, the hermit, shore and sand crab, were studied. Toxicity responses in the hermit and shore crab were quite similar. Both exhibited a high resistance to effluent toxicity; in all dilutions survival was essentially 100 percent over 96 hours. In the sand crab, however, survival was distinctly affected by sewage effluents in dilutions below 1:20. The difference in toxicity response was assumed to be related to the normal habitat of the three species. The shore and hermit crabs live in a constantly exposed habitat, while the sand crab typically remains buried during much of its life. Resistance to change (tolerance) is built into the first two crabs but is lacking in the third.

16. Three species of shrimp, the bay, pink ghost and broken-back shrimp, were studied in the static bioassay tests. Adult individuals of the first two species and larval shrimp of the third species were assayed. The bay shrimp appeared to be the most sensitive of the three. Effluent effects were significant at all dilutions less than 1:100 for the bay shrimp, while the pink ghost and broken-back shrimp exhibited high survivals (greater than 90 percent) in all dilutions except pure effluent. The high toxicity response in the bay shrimp, however, was difficult to separate from a general low toler-

ance to laboratory experimentation as evidenced in the control dilutions.

17. Survival in the turban snail, purple sea urchin and horse mussel was 100 percent in all dilutions tested. The bent-nosed clam also exhibited a high resistance to possible effluent toxicity. Only at dilutions below 1:1 was a slight toxicity measured in bent-nosed clam bioassays.

18. Dilutions necessary to insure 90 percent survival were calculated from bioassay results of the invertebrate studies. In all but four species the test organisms always had survivals greater than 90 percent. Of the remaining four species the bay shrimp was most sensitive and required dilutions greater than 1:100 for 90 percent survival. At the other end the bent-nosed clam required dilutions no greater than 1:1 for 90 percent survival.

19. Composite San Francisco effluent was judged to be relatively nontoxic to all test species until dilutions less than 1:20 were studied. Furthermore, only the sanddab and bay shrimp exhibited mortalities as high as 50 percent until test organisms were subjected to dilutions less than 1:2.

20. Environmental chamber bioassays were conducted to study the effects of municipal effluent on early life stages of a variety of organisms. Egg hatching studies and larval experiments with invertebrates constituted the bulk of the environmental chamber research.

21. Egg hatching experiments in the environmental chamber were conducted with eggs from the Dungeness crab, *Cancer magister*. The environmental chamber tests were static bioassays which were conducted for 96 hours. In these tests only dilutions equal to or greater than 1:20 were studied. Higher concentrations of effluent in small experiments caused the eggs to spoil, probably as a result of high bacterial concentrations.

22. Egg hatching in the controls and 1:100 dilutions produced hatches over 85 percent of the total viable eggs introduced at the beginning of the experiments. Dilutions of 1:50 and 1:20, however, had a significantly lower hatch and never produced viable hatchings over 45 percent. Lower percentage hatches in the 1:50 and 1:20 effluent dilutions appeared to be a direct result of effluent toxicity. The experiments also indicated that normal egg hatching for a single crab occurs over a period of about two days.

23. Larval studies were conducted on hatches from invertebrate eggs that had no history of exposure to San Francisco effluent. During the environmental chamber studies a total of ten larval bioassays were conducted. These experiments ran from ten to fifty days and tested larvae of Dungeness crab, sand crab, bay shrimp and broken-back shrimp. Three larval stages of the Dungeness crab were studied.

24. Dungeness zoea were difficult to culture and a moderate mortality was evident in all replicates. Newly-hatched zoea exhibited no appreciable difference between survival in the control and in the lowest dilution (1:20).

Sufficient 5-day-old Dungeness zoea were available to study toxicity in only two dilutions of San Francisco effluent (1:100 and 1:50). Highest mortality in all dilutions and replicates was observed to occur during the period of metamorphosis from first to second stage. The 1:100 dilution produced a slightly higher survival than either the control or 1:50 dilution.

26. A shortage of zoea limited the bioassays on 20-day-old Dungeness zoea to two dilutions of San Francisco effluent. In these studies an initial high mortality rate was observed, but by the fourth day the mortality rate had declined. Eventual survival in the control replicates remained higher than survival in the two dilutions. The fact that survival in the 1:50 dilution was slightly higher than survival in the 1:100 dilution was accounted for by differences in zoea viability through random sampling. There was some indication that dilutions of composite effluent had a toxic effect on third stage zoea survival but the results of the experiments were not conclusive.

27. A toxic effect of San Francisco municipal effluent on survival of sand crab zoea was evident at dilutions less than 1:50. Survival during the first three days of the bioassays was approximately equal, but by the fourth day the low dilutions (1:2 and 1:10) had exhibited significantly higher mortality rates. The 1:20 dilution ultimately produced a similar high mortality after 16 days. Both the 1:100 and control exhibited moderate mortality rates throughout the experiment. However, the 1:100 dilution survival was significantly higher than the control survival throughout the experiment, indicating that low dilutions of effluent were beneficial to sand crab zoea, possibly because the effluent was providing a food source of micronutrient dietary supplement. The 1:50 dilution by the end of the bioassay appeared to demonstrate the concentration at which toxicity affects at high concentrations were equaled by beneficial responses at high dilutions.

28. Bay shrimp zoea proved very difficult to culture in the laboratory, and there was a high mortality in all tests. The control replicate possessed a slightly higher survival rate throughout the bay shrimp experiments, but the culturing diffi-

culties made it impossible to determine effluent toxicity.

29. Continuous flow bioassays were conducted for 96 hours with three-spined stickleback and first stage Dungeness crab zoea. Tests were conducted at 1:100 and 1:50 dilutions. The results of all continuous flow bioassays indicated that there was no toxic effect of San Francisco composite sewage effluent in dilutions equal to or greater than 1:50

30. A microcosm study was conducted by Dr. George Schumann with Dungeness crab larvae at 1:100 and 1:200 effluent dilutions. He found low survival in the control replicate and proportionately higher survivals in the two dilutions. He also observed that the resulting number of young *C. magister* in the effluent replicates was greater than the control replicate. He concluded that the higher survival rate in the two aquaria containing sewage effluent was the result of additional food. Young crabs were produced from eggs in all replicates at the end of 74 days. This period was considerably shorter than expected and was thought to be the result of high water temperatures in the experiment.

31. A study of hematological response in three-spined stickleback exposed to high concentrations of municipal effluent was conducted. Changes in the number of white blood cells and thrombocytes corresponded to increased effluent concentrations. The increases also appeared to be correlated to bacteria levels in the effluent dilutions. The result of the blood investigations indicated that concentrations of effluent greater than 1:10 exerted a stress on stickleback by causing changes in their blood composition.

32. A biostimulation study with plankton from the Gulf of the Farallones indicated that there was no significant increase in chlorophyll a concentrations when water samples were exposed to sewage effluent in dilutions as low as 1:20. Tests were conducted over a four day period.

RECOMMENDATIONS

To assess the ecological impact of newly proposed municipal waste discharges into the estuarine environment surrounding the City of San Francisco, it has been necessary to collate information from many different sources. The majority of this information has come from literature reviews of San Francisco resources, field investigations of San Francisco Bay and the Gulf of the Farallones, and laboratory studies of toxicity and biostimulation on representative marine and estuarine organisms. In addition, useful information has been obtained from a review of the literature relating to the influence of waste discharges in other marine environments. Of particular value in predicting the possible ecological effects of a submarine outfall in the Gulf of the Farallones was a review of the biological literature on Pacific Coast marine waste disposal prepared for the City and County of San Francisco by Dr. Wheeler North. This review is presented in Volume 2, Data Supplement.

The recommendations derived from the ecological investigations of this study are presented in three sections. The first section is composed of ecological design criteria for proposed outfalls and establishes some ecologically significant parameters of size and quality for municipal discharges. The criteria developed in this section were created to insure that any new municipal waste discharge into the waters surrounding the City of San Francisco would not detrimentally affect the marine environment.

The second section discusses the scope and onjectives of a recommended monitoring program for future waste discharges. This section establishes the need for continued field surveys both before and after any new outfall is constructed.

The third section suggests additional field and laboratory investigations that have been indicated by the present work program or by other studies.

Ecological Design Criteria

The ecological design criteria for the discharge of primary-treated municipal wastes to the marine environment were developed from the results of field studies in San Francisco Bay and the Gulf of the Farallones and extensive laboratory bioassays of San Francisco municipal effluent. In addition, performance studies of existing outfalls on the West Coast have been reviewed.

The ecological criteria for location and initial dilution of proposed outfalls relate, where applicable, to both San Francisco Bay and the Gulf of the Farallones, because many of the organisms and communities studied to develop the criteria are common to both localities.

Location. The majority of criteria that relate to location of proposed outfalls were formulated from field investigations within the Gulf of the Farallones. With regard to general area, it is ecologically desirable for any proposed municipal discharge to be placed south of a line extending westward along the centerline of the Golden Gate. This criterion was established from an evaluation of the intertidal areas surrounding the Golden Gate. south of the Golden Gate the shoreline is typically sandy beach. This habitat typically contains a low diversity of organisms and a low productivity. North of the Golden Gate the intertidal zone is rocky with a high diversity and productive biota. The existing Richmond-Sunset discharge indicates that the rocky intertidal zone can be affected by a concentrated effluent discharge. It would not be expected that the effect of any newly constructed outfall could be measured on the rocky intertidal zone, but location south of the Golden Gate provides an extra margin of safety. Regional Water Quality Control Board policy for ocean disposal recognizes the importance of location and preferentially protects rocky substrates.

Depth of water in itself is not a significant ecological design criterion. If the criteria for dilution are met then exact depth of an outfall is of secondary importance. The depth of an outfall relates to the desirability of a surface or submerged effluent field. This is discussed in a following section.

Quantity of Discharge. Studies of the ecological significance of both large and small discharges in Southern California indicate that municipal waste discharges of primary effluent greater than 200 mgd have significantly affected the marine environment. Discharges smaller than 100 mgd, on the other hand, have shown no detectable detrimental effect. It is ecologically desirable, therefore, to limit the dry weather flow from a single outfall to about 100 mgd unless a degree of treatment is provided beyond conventional primary treatment.

Dilution. Dilution criteria for proposed outfalls in San Francisco Bay and the Gulf of the Farallones were developed mainly from an analysis of the results of the laboratory program. The marine biota that were tested in the laboratory were divided by habitat areas into three groups for analysis. These groups are the intertidal community, the benthic community, and the community within the water column. The effluent dilution required to assure 90 percent survival (LD_{10}) of all species in each habitat was determined. If it was impossible to affix a dilution requirement for 90 percent survival, the highest dilution which demonstrated any significant effluent response was determined (Tables 5-12 and 5-14). The most sensitive organism from each habitat was chosen as the indicator organism. A safety factor of 10 was then applied to the calculated LD_{10} for each indicator organism in order to determine the ecological dilution criteria for each habitat.

To protect the intertidal community, no municipal effluent should be present at the shoreline or in shallow water (less than ten feet) in dilutions less than 1000 to 1 over a 24 hour period. This criterion is the most restrictive of the dilution criteria but was developed to protect the intertidal biota. The indicator organism in the intertidal and shallow waters was the bay shrimp, which required dilutions of 100 to 1 to insure 90 percent survival of the test animals in the laboratory.

Benthic populations should not receive sustained exposure to concentrations of primary-treated municipal effluent greater than 500 to 1. The indicator organism in the development of this criterion was the gravid Dungeness crab. Egg hatching survival appears to be affected detrimentally when effluent concentrations exceed 50 to 1. The period of high sensitivity of Dungeness crab to municipal effluent was only during the egg carrying period, late October through January. Adult Dungeness crab never appeared to be detrimentally affected by effluent dilutions as low as 10 to 1.

Plankton and fish populations in the water column should not be exposed to dilutions of municipal effluent less than 100 to 1 on a short term basis (24 hours) or less than 200 to 1 for long term exposure. The indicator organism for the development of water column dilution requirements was the sculpin. This organism required minimum dilutions of 20 to 1 over four day exposure to guarantee 90 percent survival of test animals. Short term exposure (less than 24 hours) was found to produce little or no acute toxicity in the test fish.

Degree of Treatment. The recommendations of this study are based on experimental work performed on a composite effluent from the city's present treatment plants, and the recommendations therefore presuppose treatment at least equivalent to the present level. Most important from the standpoint of protecting the benthic community is adequate removal of settleable solids. Studies have shown that deposition of sewage solids on the ocean floor adversely affects the benthic population. If the emission of settleable solids is adequately controlled, the dilution criteria will adequately protect the biota in all other respects.

Wet Weather Effluent Field. For large intermittent wet weather effluent discharges it is ecologically desirable to have a surface field because there is a strong movement away from the shoreline. This transport would increase protection for the intertidal and benthic habitats which are the areas most sensitive to effluent impact. The requirement for a surface field is only a secondary protection criterion if all ecological dilution criteria are met.

Outfall Orientation. The diffuser and pipeline should be constructed in a manner which will not impede the movement of benthic animals. The outfall should have no dead end corridors or obstructions which would result in a trap to mobile benthos or bottom dwelling fish. Known migrations of invertebrates and fish into and out of San Francisco Bay suggested this criteria. Many of these migrations occur during reproductive periods, which emphasizes the need for an unobstructed path for non-swimming organisms in order to maintain population levels. In British Columbia Dungeness crab are know to migrate inshore during breeding periods. The migration has not been established in the Gulf of the Farallones for Dungeness crab, but daily movement of crabs is known to occur. If the outfall line provided a trap for large numbers of crabs they would fall easy prey to predators.

Safety Factors. The ecological design criteria contain a number of built-in safety factors which provide added insurance that the biota will be protected from adverse changes in the environment due to the addition of a new waste discharge. The first two safety factors relate to the choice of dilution criteria. First, the use of LD_{10}, or the first indication of any possible effluent effects, provides a conservative estimate of effluent impact. In many cases it would be possible to have a ten percent mortality in the test bioassays solely through random distribution of diseased or injured test organisms. Organism adaptation to experimental design alone might also produce a ten percent mortality in one or more of the test dilutions. Second, the use of a 10-fold multiplication factor for determination of the recommended habitat dilutions automatically creates safety factors in the ecological design criteria.

A safety factor of 10 was used to account for the fact that the most sensitive organisms might not have been tested and to account for possible acute toxicity and long-term toxic affects that could not be measured in the laboratory. The multiplication factor of 10 was chosen on the basis of a realistic assessment of the difficulties in translating laboratory work into universal field applications. In addition, the factor represents a deliberate attempt to take a conservative approach to protection of the marine environment.

The third safety factor, built into the ecological design criteria is related to the time of exposure. All dilution criteria were developed from bioassays of organisms continuously exposed to effluent dilutions for four days or longer. This is undoubtedly an overestimate of normal exposure in the marine environment. In the environment free swimming pelagic organisms rarely are subject to continuous exposure of undesirable concentrations of waste discharges because they have the ability to leave the area. Even plankton forms are swept past outfalls with the existing currents and rarely are subject to exposure for more than a few hours. The benthos, also, is usually removed periodically from exposure to waste discharge in the marine environment by the changing tidal currents. Dilution criteria based upon 96 hour exposures are therefore conservative estimates of the potential environmental impact of a waste discharge.

The last two safety factors incorporated into the ecological design criteria are related to effluent quality. The bioassays conducted during the laboratory program studied composited primary treated effluent from the City of San Francisco. All dilution guidelines and proposed effluent quality criteria were based on a discharge of similar quality. The Department of Public Works presently plans to upgrade all discharges by the addition of chemical coagulation to the primary treatment process. The City of San Francisco has also recently adopted an industrial waste ordinance which should, in time, measureably reduce the level of toxic materials entering the city's sewerage system. Both the upgrading of treatment and the removal of toxic industrial wastes will improve the quality of effluent discharged from the City of San Francisco and will provide an additional safety factor for marine environmental protection.

Monitoring Programs

In order to document any environmental change that a new marine waste discharge might create, a comprehensive monitoring program is recommended for any new outfall. This program should start at least one year in advance of outfall construction and should be intensive during the first few years of discharge. The advance start of a monitoring program is necessary to obtain background information in the area of the discharge. The necessity for a monitoring program of considerable scope, at least over the first few years, stems from the fact that the changes which the program seeks to document will be subtle ones, if they occur at all.

Monitoring programs for both new bay and ocean outfalls would be similar in time but would be quite different in scope. The fact that an outfall in the Gulf of the Farallones would discharge into an area about which little is presently known would necessitate a monitoring program of considerably greater scope. The details of monitoring programs for bay or ocean disposal, however, must await the actual choice of outfall site and a determination of the flows to be discharged. In addition, the development of any monitoring program should include discussions with the staff of the Regional Water Quality Control Board and the California Department of Fish and Game.

Other Investigations

An ecological research program of the scope and intensity previously described could not help but suggest other investigations that would contribute to a better understanding of the marine environment surrounding San Francisco.

One important area which received limited attention in this chapter but which warrants further investigation is the mechanisms by which municipal effluents affect marine organisms. Very little work has been done in this important field. The results of studies on metabolic responses of organisms to waste discharge could influence the way in which wastes are treated prior to marine disposal.

The laboratory toxicity studies on invertebrate egg hatching and zoeal response to concentrations of municipal effluent also revealed some areas for future investigation. The incidence of prezoea hatchings and response in third stage zoea of Dungeness crab are two areas of particular interest. The whole problem of obtaining high survival rates in laboratory reared invertebrates needs further investigation.

One obvious observation concerning previous studies is the limited attention that the Gulf of the Farallones has received. Many investigations have studied the biota and abiotic environment of San Francisco Bay, but very little research has been conducted in the ocean off San Francisco. Certainly, more studies are needed in the Gulf of the Farallones if we are to understand fully the relationship between the marine resources, such as the commercial fisheries, and man's possible influences.

The present study has also indicated that very little is known about the Dungeness crab. For such an important commercial fishery it seems incongruous that the ecology of this organism has not been investigated more fully. Some of the obvious questions relate to the distribution and abundance of Dungeness crab in the Gulf of the Farallones, and a better understanding of why population fluctuations occur along the entire West Coast. Additionally, it is particularly important to understand the reason for the continuing low crab populations in the Gulf after other areas have increased. Additional study on the life history of crab in relation to pesticide levels is also indicated.

At the present time an additional study has been authorized by the City and County of San Francisco to answer some of the questions posed by the present research program. The study, which was still in progress at the time this report was written, includes sampling of the plankton at selected sites in the Gulf of the Farallones in an area of proposed waste discharge and a six month continued laboratory program on the responses of Dungeness crab to San Francisco municipal effluent. Scheduled for completion late in 1971, the new study will be published as Volume 3 of this report.

CHAPTER VI

DESIGN CRITERIA AND BASIS OF COST ESTIMATES

The selection of submarine outfall designs must be made from a literally infinite combination of possible locations, flows and pipe designs. The evaluation of reasonable alternatives must be made on the basis of design and cost criteria which are applicable to all projects. Using these criteria, alternative projects can be evaluated and compared on the basis of cost and performance.

DESIGN CRITERIA

The factors which govern the design, location and successful performance of a submarine outfall may be divided into three classifications: oceanographic, ecological and physical. Oceanographic design criteria include those physical oceanographic factors such as currents and water density which influence the performance of an outfall. Ecological design criteria define the conditions which the discharge must meet to avoid a harmful effect on the marine environment. Physical design criteria refer to factors such as waste composition and flow rate, and the characteristics of pipelines and diffuser systems.

Oceanographic Design Criteria

The objective of submarine outfall construction is the discharge of wastes in a manner which will meet the water quality objectives of the regulatory agencies and the design criteria established by the ecological study. The location and design of an outfall which will meet this objective is strongly influenced by the oceanographic characteristics of the Central Bay and the Gulf of the Farallones. Oceanographic design criteria which pertain to both the Central Bay and the Gulf of the Farallones are as follows:

1. For dry weather discharges, the fall season represents the design condition because:
    a. Water clarity is greatest.
    b. Surface net advection is lowest.
    c. Density stratification is least pronounced because of low fresh water inflow, and the tendency of an effluent field to rise to the surface is greatest.
    d. Atmospheric and water temperatures are at the annual high, and recreational use of shore areas is likely to be the greatest.
2. For wet weather discharges the winter season represents the design condition. During the winter period of high fresh water runoff:
    a. Water clarity is lowest.
    b. Surface net advection is highest.
    c. Density stratification is most pronounced.

Oceanographic criteria which apply only to the Gulf of the Farallones may be summarized as follows:

1. To achieve a continuously submerged effluent field the outfall diffuser must be located outside the bar in 80 ft or more of water.
2. A surface field released at any point inside the bar in a water depth greater than about 60 ft will be advected seaward.
3. The bar area itself is too shallow to permit either surface installation of a major pipeline or good initial dilution for a major effluent discharge.
4. Effluent discharged through a properly designed diffuser located west of the mouth of the Golden Gate will have no measurable effect on the bay.
5. Floatable material released west of the mouth of the Golden Gate will not enter the bay.
6. Any dry weather discharge to the Gulf of the Farallones should be located at least one mile offshore:
    a. To avoid the nearshore currents which have a net bayward displacement.
    b. To place a surfacing field beyond the limit of easy visibility from shore.
    c. To increase the minimum shoreward travel time.
7. A wet weather discharge might suitably be made less than one mile offshore near the mouth of the Golden Gate in an area where the effluent field would be entrained in the westward-moving surface water mass.
8. An outfall and diffuser in the high current and unstable bottom area near the mouth of the Golden Gate will cost more per unit of length than in areas of lower currents.
9. The dissolved oxygen resources of the surface waters of the Gulf of the Farallones are greater outside the bar than inside the bar.

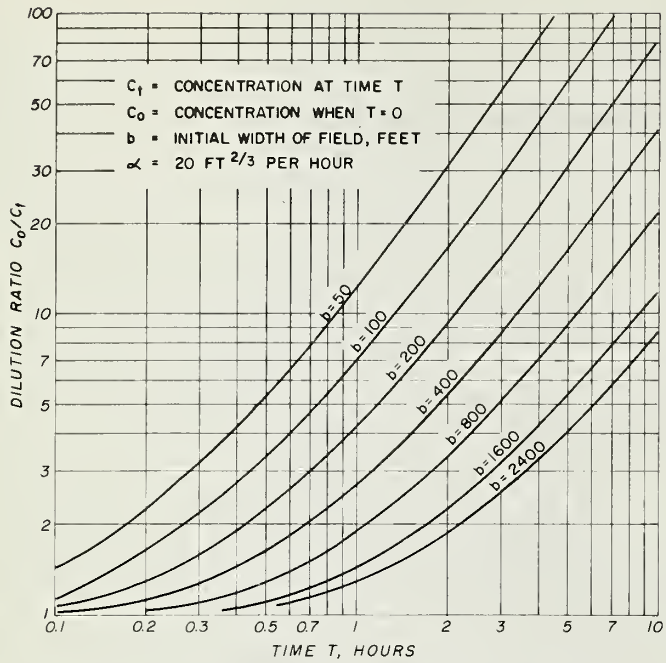


Fig. 6-1 Physical Dilution of a Sewage Field by Turbulent Diffusion in the Gulf of the Farallones

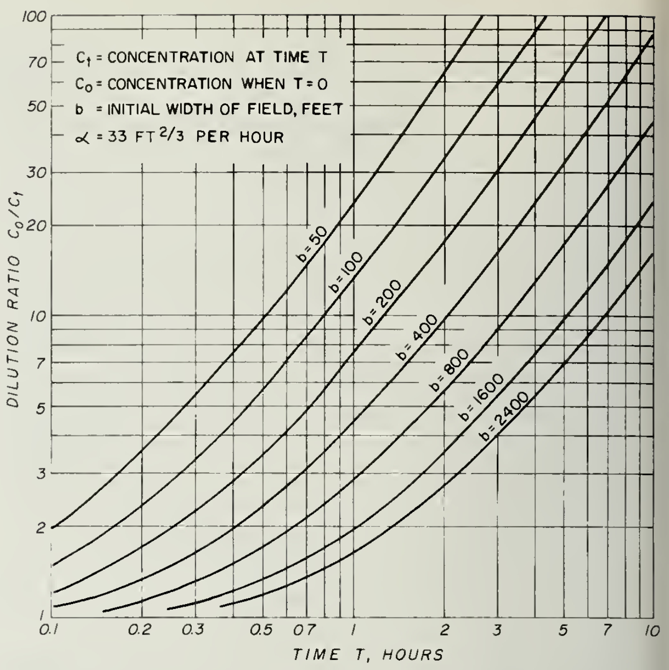


Fig. 6-2 Physical Dilution of a Sewage Field by Turbulent Diffusion in San Francisco Bay

10. A surface effluent field in the Gulf of the Farallones wil disperse horizontally in accordance with the formula $k= 20\,L^{4/3}$ sq ft/hr (Fig 6-1).

Oceanographic criteria which apply only to the Central Bay may be summarized as follows:

1. Net advection of the surface layer in the Central Bay is seaward at all times of the year. Seaward advection is weakest in the summer and fall and strongest during periods of high runoff.

2. Surface advection in the bay south of the Golden Gate Bridge is much weaker than in the Central Bay, but still has a net seaward vector at most times and stations.

3. Surface drift of floatables released in the Central Bay is seaward at all seasons. No significant deposition will occur along the bay shoreline, and the distribution along the ocean shoreline will be approximately the same as for an ocean release.

4. Density stratification is sufficient to keep an effluent field submerged most of the time at initial dilutions of 100 to 1 or greater. At times in summer and fall, however, there is no density gradient, and the effluent field will surface.

5. A surface effluent field in the Central Bay will disperse horizontally in accordance with the formula $k=33L^{4/3}$ sq ft/hr (Fig. 6-2).

6. Dissolved oxygen resources of the Central Bay are in excess of the lower limiting values established by the Regional Water Quality Control Board and recommended by Bay-Delta Program.

7. Tidal exchange at the Golden Gate brings 20 to 30 x 10^9 cu ft of new ocean water into the Central Bay each 25-hr tidal cycle during the dry weather months, and up to two or three times that amount in wet weather.

8. Tidal exchange at Alcatraz Channel brings 15 to 25 x 10^9 cu ft of new water past that site each 25-hr tidal cycle in dry weather months.

Ecological Design Criteria. A number of worthy water quality objectives have been set forth by the control agencies to prevent adverse ecological effects from marine waste discharges. Because of a lack of definitive information on the acute and chronic effects of waste discharges on marine biota, these water quality objectives are generally couched in general terms which require subjective evaluation. The ecological investigations described in Chapter 5 of this report were undertaken for the purpose of defining in specific terms the probable effect of a waste discharge to the Gulf of the Farallones. The results of the field and laboratory investigations, together with the results of similar investigations by others, were then used as design criteria to plan waste discharges in a manner which will avoid adverse ecological effects.

The ecological design criteria were presented in Chapter 5 and are listed below in summary form. The criteria can be separated into two parts. First and most important are those criteria which relate to the dilution necessary to avoid adversely affecting the marine biota. If these criteria are met, the second part, related to preferred location of an outfall, is less important. The first four criteria listed below relate primarily to dilution, and the last four to location or method of construction. All criteria are based on the assumption that future discharges will be equivalent in toxicity to the present chlorinated primary effluent. In translating the results of field and laboratory tests into the design criteria listed below, a factor of safety of 10 has been employed.

1. Where possible, dilutions of sewage effluent along the shoreline or in shallow water should not be less than 1000 to 1 for more than 24 hours at a time.
2. Gravid Dungeness crabs appear to be vulnerable to the effects of exposure to sewage effluent. The benthos in areas where gravid crabs may be present should not receive sustained exposure to effluent in dilutions less than 500 to 1.
3. Plankton and fish populations should not be exposed to dilutions of effluent less than 100 to 1 for more than 24 hours or less than 200 to 1 for long term exposure.
4. Deposition of sewage solids on the ocean floor should be avoided. Settled material of sewage origin has been demonstrated to have a negative effect on benthic populations.
5. From the standpoint of protecting the marine ecosystem in the Gulf of the Farallones, a surface effluent field is preferable to a submerged field for two reasons:
    a. A surface field will be transported away from intertidal areas.
    b. A surface field provides the greatest factor of safety for protection of the benthos.
6. As a general rule, dry weather discharges should be limited to about 100 mgd per outfall. Evidence from Southern California shows that larger discharges have had a measurable adverse effect on the marine environment.
7. Since rocky intertidal areas have a greater diversity and productivity than sandy beaches, a preferred location for an outfall in the Gulf of the Farallones would lie south of a line extended westward along the centerline of the Golden Gate.
8. Submarine pipelines and diffusers in the Gulf of the Farallones should be constructed in a manner which will not impede the periodic shoreward migration of breeding Dungeness crabs and certain other benthos.

Sewage Design Data

All computations in this report assume that sewage flows will be as shown in Tables 6-1 and 6-2. Table 6-1 presents the design flow conditions for the city's three present water pollution control plants. Table 6-2 represents the wet weather flows which will be generated in the three major drainage areas of the city, shown in Fig. 2-1, and identified as the Richmond-Sunset zone, the Southeast zone and the North Point zone. The wet weather flows shown in Table 6-2 are based on the impoundment and later slow release of major storm flows. This procedure will reduce the incidence of overflow of untreated storm water to eight times per year or less, depending on the impoundment volume. The manner in which this will be accomplished is the subject of a separate study by the San Francisco Department of Public Works.

Information on the composition of dry weather sewage flows was taken from the March, 1971 report by Brown and Caldwell[30] describing operation and performance of the city's three existing water pollution control plants. Information on the composition of wet weather flows was taken from a report by Engineering Science, Inc., dated July, 1971.[33]

Outfall Design Criteria

Submarine outfalls are designed to carry the projected future peak flow from the area to be served, as defined in Tables 6-1 and 6-2, and to diffuse the waste stream into the receiving water by means of multiple outlet ports. Diffusers are designed in accordance with the basic principles set forth in Chapter 3 to achieve the degree of dilution judged appropriate for a particular site and waste flow.

Four factors control the amount of initial dilution which can be achieved. These are water depth, port diameter, port spacing and initial jet velocity. The latter factor is a function of waste flow and the number of diffuser ports. As a practical matter, each of these factors has a limiting value. Water depth over the outfall pipe must be sufficient to avoid interference with navigation at extreme low water. This depth is determined on a case-by-case basis by the Corps of Engineers, but is never less than about 40 ft in navigable waters. Port diameter should not be less than 2-1/2 inches

Table 6-1 Design Flows at Existing Treatment Plants

Design flow condition	Design flow rate, mgd		
	North Point WPCP	Southeast WPCP	Richmond-Sunset WPCP
Dry weather			
Present minimum	30	9	8
Present average	60	20	20
Present peak	110	28	33
Future average[a]	74	24	27
Future peak[a]	134	57	54
Wet weather			
Present peak	160	47	46
Future peak[b]	200	70	70

[a] Year 2020.

[b] Hydraulic capacity of treatment plant.

Table 6-2 Design Wet Weather Flows

Point of discharge	Flow rate, wet weather master plan		
	Flow by zones, mgd[a]	Plan 1,[b] mgd	Plan 2,[b] mgd
Mile Rock			100
R-SWPCP		690	70
Lake Merced			520
Total, Richmond-Sunset zone	325		
Islais Creek		115	115
Total, Southeast zone	330		
NPWPCP		200	200
Total, North Point zone	350		
Total	1005	1005	1005

[a] Based upon a treatment rate of 0.10 inches per hr equivalent rainfall.

[b] Plans 1 and 2 involve inter-zone transport of wet weather flows.

to minimize the possibility of clogging. For this study minimum port diameter has been set at 3 inches. For small port diameters the practical limit on port spacing is about 6 to 8 ft on alternate sides of the pipe. This spacing reduces the interference of adjacent jets to a minimum and gives the maximum initial dilution consistent with economical diffuser length. Initial jet velocities greater than about 25 fps produce very little additional dilution and can be achieved only at the expense of greatly increased head requirements. For this study 25 fps, which produces an orifice head loss of about 10 ft, was used as the upper limiting value on port velocity.

All of the above factors combine to indicate that a single outfall and diffuser has a practical flow range of about 10 to 1. For greater flow ranges, either the head requirement is unacceptably high at high flows or the pipe velocities are unacceptably low at low flows.

Submarine outfall lines are assumed to be constructed of reinforced concrete pipe with flexible gasketed joints. Joints are of the confined round rubber gasket type with concrete bell and concrete spigot cast integrally with the pipe. Gaskets are not permitted to support the pipe but keep the joint tight under all normal conditions of service, including expansion, contraction and normal settlement. All outfalls are provided with a firm foundation and suitable anchorage. For outfalls constructed inside the bar at the mouth of the Golden Gate, it is assumed that the entire diffuser section and all pipe laid with less than 5 ft of cover is constructed on piles. Outfalls are designed to permit periodic cleaning and flushing as found necessary by operating experience. Wet weather outfalls are designed to prevent the build-up of marine growth inside the pipe during the periods when the outfall is not in use. Specific details of design, anchorage or construction methods require extensive investigation of local conditions and are beyond the scope of this report.

CONSTRUCTION COSTS

Construction costs presented in this report are based on preliminary layouts of the proposed outfalls. For estimating purposes, heavy reliance has been placed on actual costs of major outfalls constructed in recent years. These costs have been adjusted to reflect present price levels and local conditions. Local marine contractors were consulted on specific questions.

In considering the construction cost estimates it is important to realize that changes during final design will alter the totals to some degree, and that future changes in the cost of material, labor and equipment will certainly cause comparable changes in the estimated costs. On the other hand, since the relative economy of alternative projects can be expected to change only slightly with an increase or decrease in general construction costs, decisions based on present cost comparisons should remain valid.

Construction costs can be expected to undergo long-term changes in keeping with corresponding changes in the national economy. The best available barometer of these changes is the Engineering News-Record (ENR) construction cost index. It is computed from the prices of structural steel, portland cement, lumber and common labor, and is based on a value of 100 in the year 1913.

As indicated by the curve on Fig. 6-3, which portrays the trend of the ENR index since 1940, nationwide construction costs have been steadily increasing for many years. Since 1965 the rate of rise has steepened considerably, and now stands at 13 percent per year. This figure also shows that the ENR index for the San Francisco area has risen more rapidly than the national average.

For the purposes of this report, estimated costs are based on an ENR index of 1900, a level that is expected to be reached in San Francisco during 1972. Costs presented in this report may be related to those at any other time by applying the ratio of the then prevailing ENR index to 1900. The reader is cautioned to make adequate allowance for cost increases in estimating the cost of future construction.

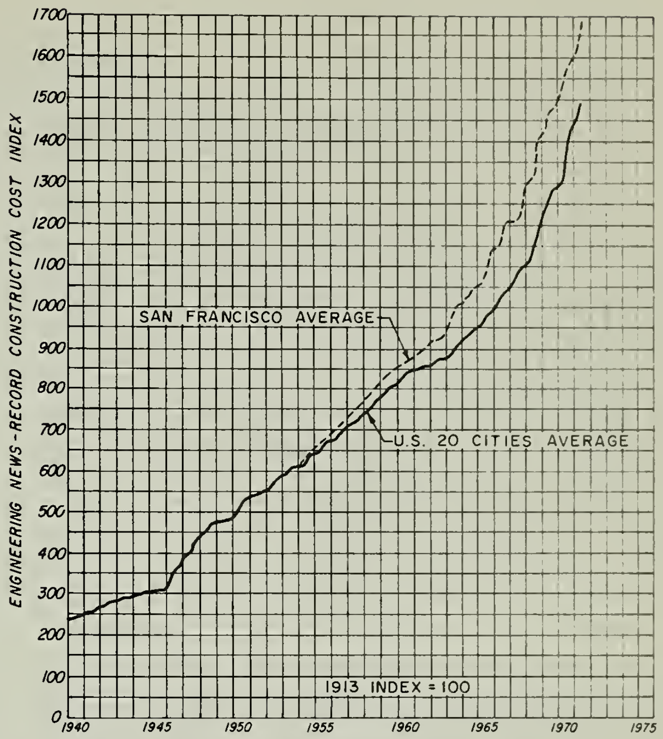


Fig. 6-3 **Engineering News-Record Construction Cost Index**

Submarine Outfall Sewers

Unit costs for submarine outfall sewers (Fig. 6-4) are based principally on the evaluation of known costs of submarine outfalls constructed in areas with generally similar oceanographic characteristics to those here considered. The curve reflects costs for outfalls terminating at a moderate depth of less than 200 ft, and includes construction of a straight diffuser section of normal length at the outlet end. Costs are for a predominantly sand bottom with few obstructions. Where extensive amounts of rock are encountered at a submarine outfall location, costs will be higher than shown in Fig. 6-4. Each such case must be estimated separately.

Contingencies

Contingent costs are considered in two forms, identified as project contingencies and construction contingencies. Project contingencies allow for the uncertainties unavoidably associated with pre-

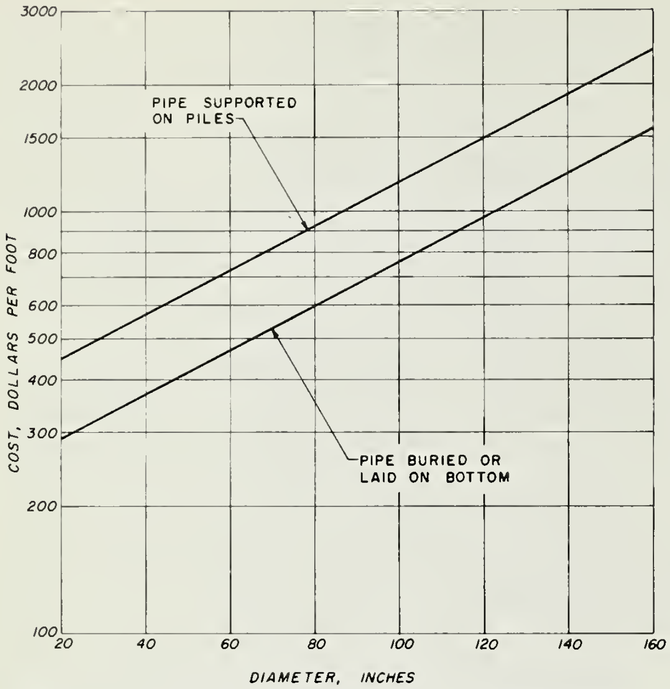


Fig. 6-4 Unit Cost of Submarine Outfall Sewers

liminary design. Such factors as foundation conditions, necessity for special construction methods, and variations in final lengths of pipelines are a few of the many items which may increase contract costs and for which allowances must be made in preliminary estimates. For project contingencies, an allowance of 15 percent is applied to all projects. Construction contingencies amount to 10 percent and represent the normal allowance for extra work which the City of San Francisco routinely employs on all construction contracts. The total allowance for contingencies in the construction cost estimates presented in this report is therefore the sum of project contingencies and construction contingencies, equivalent to 25 percent of each project.

Engineering Costs

The cost of engineering services for major construction projects may include special investigations, predesign reports, surveys, foundation explorations, location of interfering utilities, detailed design, preparation of contract drawings and specifications, construction inspection, material testing and final inspection of the completed work. Depending on the size and type of the project, total engineering costs may range from 7 to 15 percent of the contract cost. The lower percentage normally applies to large projects and those which do not require a large amount of preliminary investigation. Because of the unusually high expenses involved in underwater inspection, engineering costs on submarine outfalls normally run about 5 percent higher than for other construction projects of comparable dollar value. For the purpose of this report engineering costs for submarine outfalls are taken as 16 percent of the contract cost. When applied in sequence, construction contingencies and engineering amount to 45 percent of the basic contract cost. All construction cost estimates developed in this report include an allowance of 45 percent for contingencies and engineering.

CHAPTER VII

INVESTIGATION OF ALTERNATIVE PLANS

Previous chapters of this report have been devoted to a description of the factors which influence the marine disposal of liquid wastes from the City and County of San Francisco. The existing sewerage system has been described, and present and future waste flows have been presented as developed in independent studies by the San Francisco Department of Public Works. The basic mechanisms which influence submarine outfall performance were explored, and the water quality criteria set forth by the regulatory agencies were presented. Chapter 4 presented the results of an oceanographic investigation which defined the factors affecting liquid waste disposal to the Central Bay and the Gulf of the Farallones. Chapter 5 presented the results of biological investigations from which design criteria were developed to permit planning of waste disposal projects which will not cause damage to the marine ecosystem. In Chapter 6 all design criteria were summarized and the basis for estimating construction costs was set forth. Briefly, the report thus far has been concerned primarily with the presentation of background material necessary to the formulation and analysis of various plans for the marine disposal of liquid wastes from the City of San Francisco.

This chapter deals with the determination of the capacities, locations and costs of submarine outfall sewers required to dispose of the city's dry and wet weather effluents in accordance with the design criteria previously set forth. The reader is reminded that this report deals only with the characteristics of the receiving waters and the feasibility of disposing of effluent therein. Neither the feasibility nor the relative economy of transporting effluents to the land terminus of the various submarine outfalls is considered. While the degree of treatment necessary for disposal at different sites is discussed, no evaluation is made in this report of the relative merit of increased treatment versus additional transport costs.

Alternative Flow Conditions

While this report was in progress the City and County of San Francisco Department of Public Works was proceeding independently on its master plan for the solution of both dry weather and wet weather sewage disposal problems. The city's basic approach was to divide the entire city into zones based on drainage patterns, consider the total dry and wet weather flows from each zone, and then consider the flows from the zones with bay drainage which might feasibly be transferred to a point of ocean disposal. The three zones, as shown on Fig. 2-1, are the North Point zone, the Southeast zone and the Richmond-Sunset zone.

The sewage flows anticipated from each zone, as well as the flows for various combinations of interzone transport, are shown in Tables 6-1 and 6-2. The peak flows listed in Table 6-1 represent the hydraulic capacities of the existing treatment plants, and occur only in wet weather. The peak wet weather flows listed in Table 6-2 are based on storage of storm peaks and slow release through treatment works of a type as yet unspecified. This method of handling wet weather flows is capable of reducing the incidence of bypassing to eight or less times per year. High rates of rainfall will result in the bypassing of excess storm flows at certain points yet to be established.

North Point Zone. Referring to Tables 6-1 and 6-2, the projected peak wet weather flow from the North Point zone is 350 mgd. Of this amount it is anticipated that 200 mgd will be treated in the existing North Point Water Pollution Control Plant. The remaining 150 mgd will be either treated in the North Point zone in a separate wet weather treatment facility or transferred to the Richmond-Sunset zone. A submarine outfall designed to convey and disperse the dry weather flow from the North Point zone should therefore have a capacity of at least 200 mgd, equivalent to the maximum treatment plant capacity. If the treated wet weather flow is to be included in the same outfall, the outfall capacity under wet weather conditions must be 350 mgd. If a separate wet weather outfall is constructed for the North Point zone its capacity should be 150 mgd, and it will be used only during periods when the total effluent flow from the zone exceeds 200 mgd.

Southeast Zone. Projected peak wet weather flow from the Southeast zone (Table 6-2) is 330 mgd. Capacity for the present plant and submarine outfall is 70 mgd, leaving 260 mgd for intermittent discharge during wet weather. Up to 215 mgd of the wet weather discharge is being considered for transfer to the Richmond-Sunset zone. If that entire amount is transferred, the intermittent discharge in the Southeast zone will not exceed 45 mgd.

Richmond-Sunset Zone. The peak wet weather flow generated in the Richmond-Sunset zone is 325 mgd (Table 6-2), of which 79 mgd will be treated in the existing Richmond-Sunset Water Pollution Control Plant. Thus, if the zone is considered as a separate entity, a wet weather outfall will have to convey and disperse an intermittent flow of up to 255 mgd. However, the City is considering the possibility of transferring a part or all of the dry weather flow, as well as a portion of the wet weather flow, from the other two zones to the Richmond-Sunset zone for final disposal. These possible transfers compound the number of options which must be considered for outfalls. The different options for the Richmond-Sunset zone are summarized in Table 7-1. Options one through four are possible combinations of dry weather flows and points of disposal. These wet weather flows are intermittent flows in excess of the capacity of the treatment facilities, and options one through four may therefore occur in any combination with options five through seven. In other words, inter-zone transfer of peak dry weather flows may take place independently of the inter-zone transfer of wet weather flows, and vice versa.

Development of Plans

The first step in the preliminary design of an outfall sewer is the selection of alternative sites for analysis. Initial selection is usually made on the basis of physical factors of geography, geology and submarine topography. Using the oceanographic data available for the area under consideration, the alternative sites are then evaluated to compare their effectiveness in disposing of effluent in accordance with the design criteria set forth in Chpater 6. Finally, the alternative sites are compared on the basis of cost, performance and other factors, and the preferred site is selected for a detailed design analysis of the recommended outfall line.

The repetitive mathematical calculations involved in ocean outfall analysis lend themselves particularly well to computer application, and three computer programs developed by Brown and Caldwell were used in outfall evaluation. These programs enabled the complete analysis of an outfall diffuser for hydraulic characteristics, initial dilution and subsequent dilution in a matter of minutes. Computer analysis made if possible to run several analyses for each flow condition, permitting the evaluation of the effect of a number of different variables on outfall performance. The factors included in the programs for solution of initial and subsequent dilution were presented in Chapter 3.

Table 7-1 Richmond-Sunset Zone Flow Options

Option no.	R-S zone		Transferred from				Total flow		Discharge point
	WWF	DWF	SE zone		NP zone				
			WWF	DWF	WWF	DWF	DWF	WWF	
1		70					70		Lands End
2				70			70		Lake Merced
3		70		70			140		Lands End
4		70		70		200	340		As required
5	255							255	Lands End
6	255		215		150			620	Lands End
7a	100							100	Lands End
7b	155		215		150			520	Lake Merced

DWF - Dry weather flow, mgd. DWF for each zone is equal to the peak capacity of the zone's treatment plant.

WWF - Wet weather flow, mgd, in excess of DWF. See table 6-2.

NORTH POINT ZONE

The Regional Water Quality Control Board in 1970 specified that the City of San Francisco must develop a solution to its dry weather flow problems in the North Point area by January 1, 1973. Since this time span is very short for the study, design and construction of a major project such as a large submarine outfall, the beginning of design of an outfall for the effluent from the North Point Water Pollution Control Plant could not await the publishing of this report. Accordingly, an interim report containing recommendations for the North Point outfall was prepared as soon as the oceanographic and ecological field work had been completed. Shortly after the submission of the interim report, Brown and Caldwell was engaged to design the recommended outfall. Design proceeded concurrently with the preparation of this report and was approaching completion as the final report was written. This report therefore not only summarizes the information contained in the interim report on the North Point outfall, but also describes the project as developed in final design.

Comparison of Alternative Sites

A preliminary investigation of the Central Bay adjacent to the North Point treatment plant indicated that two alternative sites merited detailed analysis. The two sites, together with the tentative routing of submarine outfall lines to each site, are shown on Fig. 7-1. The factors involved in the analysis of the two sites are compared below.

Physical Factors. Depth of water is an important factor in submarine outfall site selection because it strongly influences the amount of initial dilution obtainable. A level site for the diffuser section is preferable to promote even flow distribution throughout the range of flows. Soil conditions should be amenable to economical construction of the outfall line, and the bottom must be stable enough to prevent the pipe from being displaced or buried.

The deepest water in the vicinity of North Point is immediately south of Alcatraz Island, near Site B. Bottom topography indicates that Site B, at about 100 ft depth, is the deepest location at which a diffuser of the required length can be laid level at an angle greater than 45 degrees to the prevailing current. Site A lies 2000 ft closer to the plant at a depth of about 70 feet. It will also accommodate a level diffuser, which can be laid nearly perpendicular to the prevailing current. To take maximum advantage of the increase in initial dilution due to current, the diffuser should be laid perpendicular to the predominant current direction.

Bottom conditions in the vicinity of Sites A and B were investigated with respect to both long-term stability and possible construction problems. Sediments from a series of random grab samples collected in the vicinity of Sites A and B were previously described in the section on marine ecology. All available information led to the conclusion that construction would be routine at either site, though the swift currents would increase the cost of the work. Subsequent soil borings and sub-bottom profiles of the area, collected in the course of the design surveys, confirmed this conclusion.

Bottom stability was checked by comparing the bottom elevations along the alternative outfall routes as shown on all hydrographic surveys of the area from 1855 to present. This comparison indicated that the deep hole to the south of Alcatraz Island, the edge of which was selected for Site B, is scoured by currents passing around Alcatraz. Historically, the depth and location of the hole have shifted appreciably. Maximum depth has varied from 112 to 165 ft, and depth in the vicinity of Site B has varied from about 105 to 150 ft. Site B is therefore in an unstable bottom area which is not desirable for outfall construction. A similar check of Site A showed that the maximum historic shift of bottom elevation at any point was about 15 ft, from 61 to 76 ft. The 15-ft maximum change at Site A was comparable to the change which had occurred in bottom elevation of most other areas in the vicinity of North Point.

Hydraulics. Sufficient head must be provided at the outlet of the North Point Water Pollution Control Plant to force the maximum design flow through the outfall and the diffuser ports at high tide. If insufficient gravity head is available, an effluent pumping station must be provided. For the sake of comparison of the two sites, the same diffuser design was used in the hydraulic analysis of both outfalls shown on Fig. 7-1.

The maximum pipe diameter which can be used without encountering unacceptably low velocities under present minimum flow conditions is 102 inches. With this pipe diameter, the available head at the North Point plant outlet will permit discharge of the peak plant capacity of 200 mgd against a tide of 6.5 by gravity at Site A. At Site B, which requires a longer, deeper outfall with more pipe friction loss and more salt water density head, only about 180 mgd can be discharged against the same tidal condition.

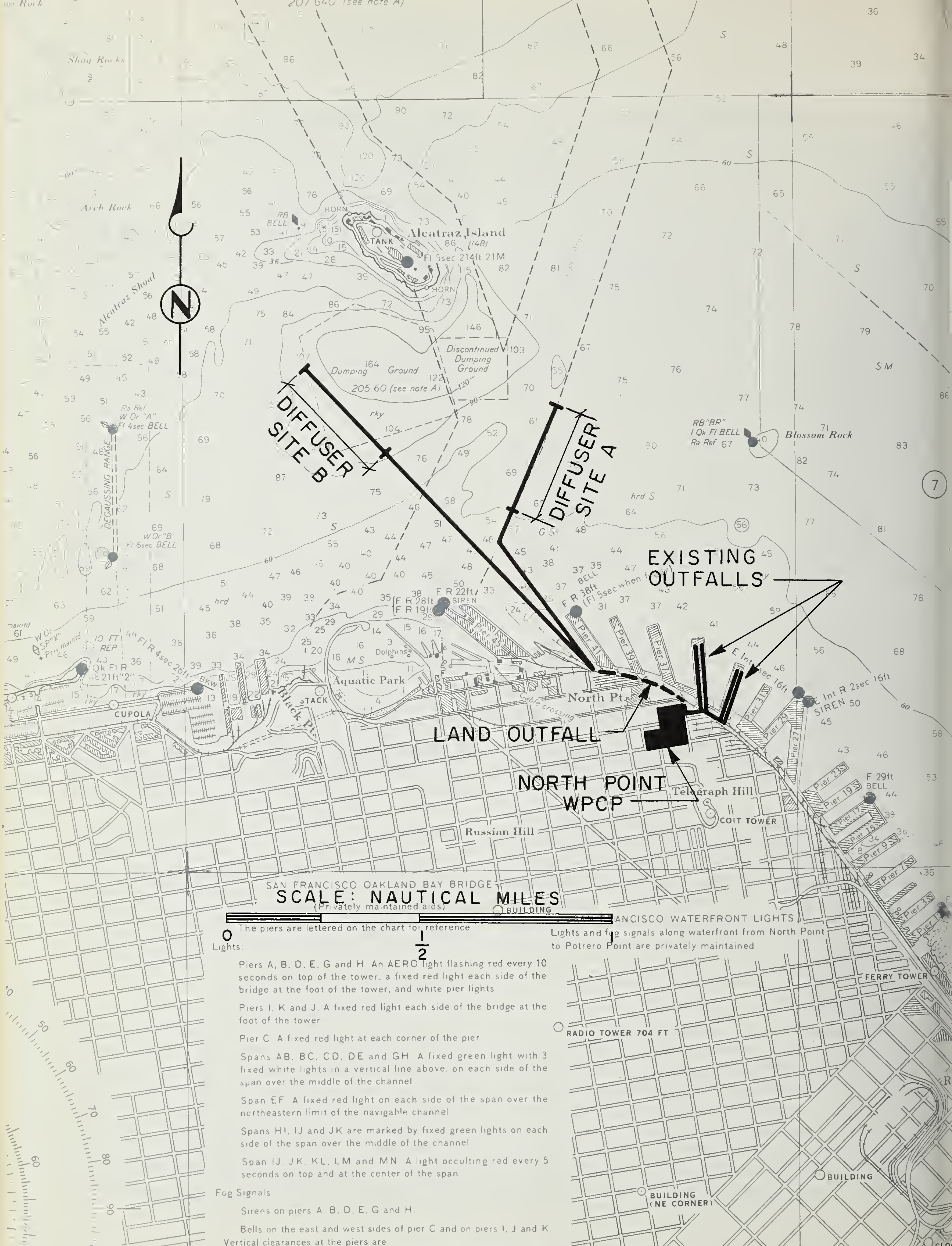

DIFFUSER SITE B
DIFFUSER SITE A
EXISTING OUTFALLS
LAND OUTFALL
NORTH POINT WPCP
SCALE: NAUTICAL MILES
0
1/2
1
N
Alcatraz Island
Dumping Ground
Discontinued Dumping Ground
Blossom Rock
Arch Rock
Shag Rocks
Alcatraz Shoal
DEGAUSSING RANGE
Aquatic Park
Black Pt.
North Pt.
Telegraph Hill
Russian Hill
COIT TOWER
CUPOLA
TACK
FERRY TOWER
RADIO TOWER 704 FT
BUILDING
BUILDING (NE CORNER)
Pier 45
Pier 41
Pier 39
Pier 37
Pier 31
Pier 29
Pier 27
Pier 23
Pier 19
Pier 17
Pier 15
Pier 9
Pier 7
Pier 3
SAN FRANCISCO OAKLAND BAY BRIDGE
(Privately maintained aids)
The piers are lettered on the chart for reference
Lights:
Piers A, B, D, E, G and H. An AERO light flashing red every 10 seconds on top of the tower, a fixed red light each side of the bridge at the foot of the tower, and white pier lights
Piers I, K and J. A fixed red light each side of the bridge at the foot of the tower
Pier C. A fixed red light at each corner of the pier
Spans AB, BC, CD, DE and GH. A fixed green light with 3 fixed white lights in a vertical line above, on each side of the span over the middle of the channel
Span EF. A fixed red light on each side of the span over the northeastern limit of the navigable channel
Spans HI, IJ and JK are marked by fixed green lights on each side of the span over the middle of the channel
Span IJ, JK, KL, LM and MN. A light occulting red every 5 seconds on top and at the center of the span.
Fog Signals
Sirens on piers A, B, D, E, G and H.
Bells on the east and west sides of pier C and on piers I, J and K.
Vertical clearances at the piers are
PIER A - 174 FT.
PIER B - 217 FT.
PIER C - 220 FT.
PIER D - 218 FT.
PIER E - 175 FT.
PIER H - 184 FT.
PIER I - 178 FT.
PIER J - 170 FT.
PIER L - 155 FT.
PIER M - 141 FT.
SAN FRANCISCO WATERFRONT LIGHTS
Lights and fog signals along waterfront from North Point to Potrero Point are privately maintained

Fig. 7-1 North Point Outfall Alternative Sites

Initial Dilution. For a given diffuser design, the initial dilution attainable at Site B is slightly better than at Site A because of the greater depth. However, dilutions well in excess of 100 to 1 can be achieved at either site with a discharge of 200 mgd, and initial dilution is not an over-riding factor in site selection.

Recommended Site. The preliminary investigations described above showed that an outfall constructed at Site B would be longer and therefore more expensive; would be laid in an unstable bottom area; would deliver less flow at the same head; and would offer no appreciable improvement in initial dilution over Site A. Site B was therefore rejected, and efforts were directed toward the development of a suitable outfall design for Site A.

Dry Weather Outfall

Consideration was given first to the development of a design at Site A for an outfall capable of disposing of the effluent from the North Point Water Pollution Control Plant. Design flows for the outfall are listed in Table 6-1. The peak flow rate is 200 mgd, the hydraulic capacity of the North Point plant. After a preliminary design had been developed for the dry weather outfall, consideration was given to the alternatives of including wet weather flows in the same outfall or constructing a separate outfall for intermittent wet weather flows.

Outfall Location. The best location for an outfall to reach Site A, the recommended site, was investigated with relation to waterfront planning, maximum protection from damage by shipping, and possible interference with structures and utilities.

Since the North Point outfall will be a costly submarine structure with a design life of 40 to 50 years, it is important that it be constructed insofar as possible in accordance with the long-range plans for development of the San Francisco waterfront area. Future plans for development of the San Francisco waterfront in the North Point area were discussed with the staff of the San Francisco Port Commission. The following points pertinent to the North Point outfall construction were raised:

1. Plans call for Piers 37 to 43 to be removed, as they are no longer strong enough for handling and storage of cargo and are used only occasionally for temporary berthing of ships awaiting berthing at another point.
2. Pier 35 and all piers to the east will remain and will be used for shipping.
3. Pier 45 substructure will remain, but the pier will be developed for a non-shipping use.
4. The Port Commission recommended that the top of the outfall pipe be not less than 55 ft below mean lower low water to assure that future shipping, which may be of deeper draft, can be accommodated.
5. A preferred route for crossing the waterfront with an outfall line runs down the dock between Piers 41 and 43. About 2400 ft of land outfall line will have to be constructed along the Embarcadero in order to reach this site from the North Point plant.

In an area as heavily traveled by commercial shipping as the Central Bay, the possibility of damage to an outfall resulting from ships anchors must be carefully assessed. The hazard can, of course, be materially reduced by constructing the outfall and diffuser in an area where ships do not normally drop their anchors. This matter was discussed with several experienced members of the Bar Pilots Association to obtain their assessment of the areas of minimal risk.

Many ships entering either a dock or an anchorage area will routinely drag their anchors as a means of reducing speed. The area east of the Blossom Rock Buoy is a designated anchorage area, and was ruled out as a possible outfall and diffuser site for that reason. Most of the anchor dragging, however, is done near the piers rather than out in the roads. The best site, therefore, is the one which is most remote from docking and anchorage areas.

Severe penalties are assessed for dragging an anchor in a cable area except in a genuine emergency; therefore, an outfall laid in or near a cable area is automatically protected to some degree. It was the opinion of the pilots with whom the matter was discussed that the best location for an outfall from the standpoint of protection against damage by anchors would be west of the cableway which runs from Aquatic Park to Alcatraz and Angel Island. The opinion was expressed that an outfall east of the cableway should be buried in the area near the piers to a depth which would prevent anchor damage. This depth was thought by the pilots to be about 10 ft.

Based on the information on waterfront planning and on the information obtained on ship traffic, the outfall route shown on Fig. 7-1 was judged to be the best route to Site A. The route is remote from active docking and anchorage areas, and the pipe will be buried at least 10 ft deep through the area immediately north of the docks.

The exposed diffuser section will be laid along the easterly edge of the cable area to take maximum advantage of the legal protection it affords. There is, of course, some unavoidable risk of damage by ships anchors. This risk must be assumed for any outfall constructed in the navigable waters of the bay.

Interferences. The only known obstructions to underwater construction in the North Point area are underwater cables laid in the cable area shown on Fig. 7-1. The best available information on the cable area indicates that there are two active and three dead underwater cables in the area. All are installed on the westerly side of the cable area, and none should offer any obstruction to the installation of an outfall as shown on Fig. 7-1.

Hydraulics and Diffuser Design. The ability of a submarine discharge to meet water quality criteria depends to a large extent upon the degree of initial dilution attainable in the rising plume of effluent discharged from the diffuser. Initial dilution is a function primarily of depth of discharge, discharge port diameter and spacing, and initial jet velocity. Jet velocity, of course, is a function of sewage flow.

If present head losses at the outlet of the North Point plant are reduced by eliminating the Parshall flume from the effluent channel and constructing a new connection from the chlorine mixing tank to the outfall line, an outfall can be constructed which will not require effluent pumping. Such an outfall will discharge the design flow of 200 mgd against a tide of 6.5 feet, which is about 0.4 feet less than the maximum tidal stage listed in the USC&GS tide tables.

Because of the limited head available for gravity flow and the relatively shallow depth at which the diffuser will be constructed, it must contain a large number of ports of small diameter spaced as far apart as practicable. During the process of final design the optimum diffuser design was determined to be 1850 ft of 102-in. pipe containing 462 diffuser ports, each 3 inches in diameter and spaced at 4-ft intervals staggered on opposite sides of the pipe. For a density structure in the receiving water which would allow the jets to rise to the surface, dilution and head loss characteristics of the outfall and diffuser will be as shown on Fig. 7-2. As the curve shows, dilution of the surfacing field at a flow of 200 mgd will be about 140 to 1. The above analyses were made for the most conservative condition, which is slack water. At average current, dilutions will be two or three times the values shown on Fig. 7-2.

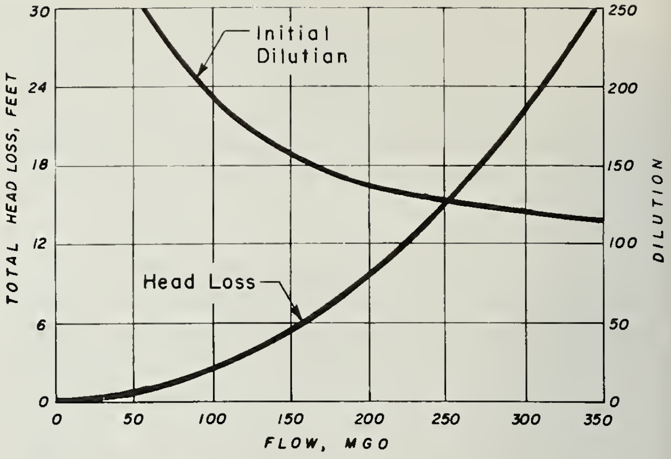


Fig. 7-2 **Head Loss and Initial Dilution Characteristics, Recommended North Point Outfall**

Pipe Design. The submarine outfall sewer will be constructed of precast reinforced concrete pipe in accordance with the design criteria presented in Chapter 6. The pipe will be laid in a trench to about the beginning of the diffuser section. The diffuser section will be laid directly on the natural bottom of the bay. The trench bottom or natural bottom will be graded by excavating through irregularities or leveling with rock as necessary to provide continuous support for the pipe.

During the process of final design a detailed investigation was conducted to determine the best method of stabilizing the outfall diffuser under shifting bottom conditions. Dr. Hans Einstein, Professor of Hydraulics at the University of California and an authority on sediment transport, was engaged as a special consultant for these studies. It was concluded that the fine sands which comprise the bottom of the Central Bay are constantly in motion under the strong currents in the area. Sand waves up to six feet high migrate past Site A. The moving sand will pass over the pipe without ill effect, and the jets through the diffuser ports will keep the port area clear so long as jet velocity is equal or greater than current velocity. Some sand may enter the pipe at minimum flows, but it should be amenable to removal by periodic flushing. Proper ballasting of the pipe as it is installed will prevent undermining and shifting of the diffuser section.

Construction Cost. Using the unit cost curve presented in Fig. 6-2, the 5000-ft submarine outfall for the North Point Water Pollution Control Plant has an estimated contract cost of $4.4 million. Allowing 45 percent for engineering and contingencies, the total project cost is estimated at $6.4 million.

Performance. The outfall design described above will produce a submerged effluent field at all times during the winter when there is strong density stratification in the Central Bay. During the summer and fall, however, there will be times when density stratification is absent and the effluent will rise to the surface and disperse as a surface field. Whether surface or submerged, the minimum dilution of the field when it reaches stability with the receiving water environment will be well in excess of 100 to 1 and the average value will be 200 to 1 or greater. This is far greater than the initial dilution objectives established by the Regional Board and by the Bay-Delta Program.

After the effluent field has reached stability in the receiving water mass, further dilution is caused by horizontal and vertical dispersion. The faster the current at the disposal point, the thinner is the initial effluent field, and the thinner the effluent field the greater is the potential for vertical dispersion. For example, at the average dry weather discharge rate of 83 mgd and an average current of 1.5 K the North Point outfall will produce a field with a depth of 4 ft. The field depth will be twice as great at half the average current, and four times as great at half the average current and twice the average flow rate. In order to affect the benthos, the effluent field must reach the bottom by vertical dispersion. Since the minimum depth in areas likely to be affected by the North Point effluent field is about 40 ft, a 4-ft deep effluent field will be diluted at least 10 to 1 by the time it reaches the bottom. With an average initial dilution of 200 to 1, the dilution at the bottom will be 2000 to 1. This analysis ignores horizontal dispersion, which occurs simultaneously with vertical dispersion and multiplies the total dilutional effect.

Referring to the ecological design criteria set forth in Chapter 6, it will be seen that initial dilution alone will meet the criterion for protection of the organisms dwelling in the water mass. Initial dilution plus vertical dispersion will exceed the 500 to 1 dilution which will assure protection of the benthos.

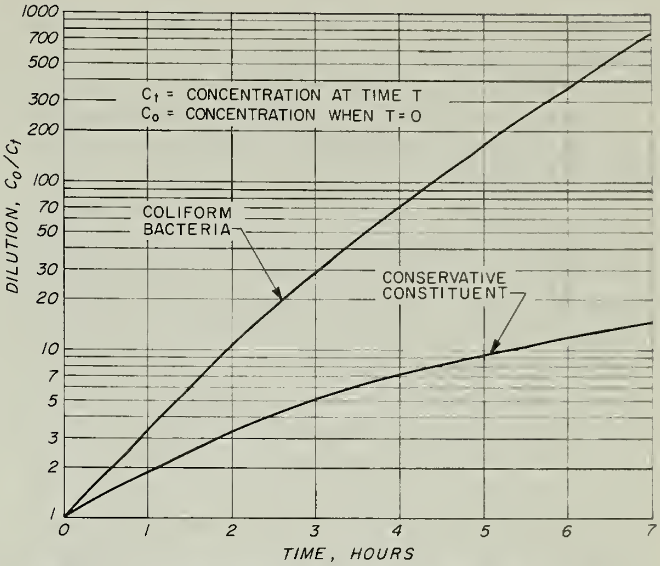


Fig. 7-3 **Horizontal Dispersion of Effluent Field, Recommended North Point Outfall**

Hosizontal dispersion of the effluent field and dispersion and dieoff of coliform bacteria will occur in accordance with the curves shown on Fig. 7-3. The ecological criterion for dilution desired to protect mudflats and shoreline areas, established at 1000 to 1 in Chapter 6, may be evaluated by considering horizontal dispersion. On the ebb tide, the effluent field will move directly through the Golden Gate in the main water mass and will not contact the shoreline. On the flood tide the effluent field will move under the bay bridge and into the South Bay, where it will approach shoreline areas of ecological concern at about the end of the flood phase. However, reference to Fig 7-3 shows that a dilution of 5 to 1 will be achieved due to horizontal dispersion alone after three hours. With an average initial dilution of 200 to 1, dilution after three hours will be 1000 to 1. In three hours at average current velocity the effluent field will travel southerly to a point about in the center of the bay opposite Central Basin, and will not reach any shoreline of ecological concern. This analysis ignores vertical dispersion, which occurs simultaneously with horizontal dispersion and multiplies the total dilutional effect.

Treatment Required Prior to Discharge

The analysis of outfall performance presented above indicates that the North Point outfall will meet the ecological design criteria established for this project while discharging a chlorinated primary effluent equivalent in quality to the present discharge. If additional treatment is required, therefore, it will be because it is required by the regulatory agencies and not because it is essential to the protection of the marine environment. Treatment necessary to meet the discharge requirements set forth in Chapter 3 is discussed below in the light of dilution attainable with the diffuser design described previously.

Settleable Solids. Efficient primary treatment will accomplish substantially complete removal of settleable solids.

Toxicity. Discharge requirements state that the effluent shall be diluted to 10 percent or less of the 96-hour TLm concentration. Present TLm values for the North Point effluent normally exceed 50 percent. Thus, for an effluent of the present quality a 20 to 1 dilution would be required. The outfall design described previously will exceed that dilution requirement by 5 to 10 times.

Floating, Suspended or Deposited Matter. The evidence obtained from surface drift studies indicates that floatables released from the North Point outfall will not accumulate along shoreline areas within the bay. Within a week, however, a portion of the conservative floatables may be deposited on the ocean beaches. Very little quantified information is available on floatables, and there is no way to estimate the proportion of organic material which will be broken up, degraded, eaten by seagulls or otherwise destroyed during a week in the surface waters of the bay and the Gulf of the Farallones. Certainly, the goal of treatment should be nearly complete removal of inorganic and conservative floating material.

The only quantitative quality objectives for floatable materials set forth so far are contained in the Bay Delta Water Quality Control Program. As stated therein, "The recommended water quality objective for floatable materials is that floating materials of waste origin shll not be present in concentrations which cause interference with identified beneficial uses, particularly esthetic enjoyment and recreational uses. As a guide it is suggested that the maximum areal concentration of oily materials on the water should not exceed 0.02 g/sq m (grams per square meter) and that concentrations of these materials on the shore areas should not exceed 0.3 g/sq m."

While the terms "oily substances" and "floatables" are at present ill defined and the techniques for measurement imprecise, it is assumed for the purpose of this analysis that the total emission of floatables from the North Point plant is measured by the laboratory test for floatables as developed by Engineering-Science, Inc., in 1965. This is the basis used for the description of floatables in the Bay-Delta Program. During the week from July 30 to August 5, 1970, the average value of floatables in the North Point plant effluent was found to be 2 mg/l. This checks quite well with the assumed total emission of floatables to the Central Bay as presented in the Bay-Delta Program.

By applying the values for initial dilution and subsequent dispersion as determined in the course of this study, and assuming that all floatable material rises to the surface within one hour after discharge, it can be calculated that the maximum concentration of floatables will occur about one hour after slack water when the surface field folds back on itself. The maximum concentration computed in this manner would amount to about 12 mg/sq m. To this concentration would be added the background value for the Central Bay as a whole under steady state conditions of release and decay. If this value is estimated at 3 mg/sq m, the maximum concentration in the vicinity of the North Point outfall would amount to 15 mg/sq m, very near the upper limit of 20 mg/sq m. suggested by Bay-Delta Program.

As a check on the calculations reported above, an analysis was made of the actual values of floatables measured in the Central Bay near the Baker Street outfall site. As reported by Engineering-Science, in Chapter VI of their draft report to the city, the average wet weather value of all floatables which could not be identified as non-sewage in origin amounted to 1.1 mg/sq m. The corresponding dry weather value, which is more pertinent to the design of a dry weather outfall for the North Point plant, was only 0.20 mg/sq m. These values, which reflect the presence of floatables presently being released from the North Point plant, suggest that the computed values for concentration of floatables released from the projected outfall are conservative.

Based on the data presently available, the following conclusions can be drawn:

1. All information on floatables is imprecise at the present time.
2. Calculations for the proposed North Point outfall, based on present effluent quality, show that floatables in a surface field may approach, but will not exceed the Bay-Delta objective of 20 mg/sq m.
3. The calculated values are probably conservative.
4. Plans for treatment at North Point should include a contingency plan for more efficient removal of floatables in the event of future need.

Background readings of suspended solids in the waters of the Central Bay are about 5 to 10 mg/l during the period of greatest water clarity, which occurs during the dry weather months. The present average suspended solids of 95 mg/l in the North Point effluent, diluted 150 to 1 at maximum dry weather flow, would add an increment of only 0.6 mg/l to the receiving waters. This represents an increase of about 10 percent measured at the point where the effluent field first surfaces. No improvement beyond primary treatment would appear to be necessary to meet requirements for suspended material. The City of San Francisco, however, is proceeding with plans to add chemical treatment at North Point to improve substantially the efficiency in suspended solids removal.

Bottom deposits will not be a matter of concern in the vicinity of the North Point outfall. Average bottom currents are in excess of one knot, and maximum values are more than twice that figure. For virtually the entire tidal cycle, therefore, velocities are sufficient to prevent the settlement of any materials not removed in the primary treatment process. This conclusion is confirmed by the imspection of bottom materials collected from the disposal area. All samples show coarse to fine sand, indicating that lighter materials are scoured from the area. Studies undertaken in connection with the design of the North Point outfall show that the bottom sand is in a constant motion.

Objectionable Aquatic Growth. In the absence of quantitative criteria for biostimulatory material, the best evidence in support of the fact that this requirement can be met is the fact that no objectionable aquatic growth has been attributed to the present North Point discharge. The proposed outfall will dilute the effluent about 10 times more effectively than does the present outfall.

Temperature, Turbidity and Apparent Color. Temperature of the effluent will create no problem. During the period of highest temperatures in the bay there is a thermocline in the Central Bay which averages one deg C. The effluent will be diffused into the colder bottom water and if it reaches the surface at all will actually have a temperature colder than the ambient surface layer.

As defined by the Regional Water Quality Control Board in its present requirements for the North Point discharge, apparent color includes any of the factors which tend to make an effluent field visible in the receiving waters. The requirements state that the apparent color of the discharge must not deviate to an objectionable extent from the natural background value. Historically, apparent color has been presumed to be defined by Secchi disc readings, and numerical values for allowable deviation from background have been proposed but never adopted.

The data presented in Chapter 4 show that an effluent field can be observed visually and measured with a Secchi disc in dilutions far in excess of those attainable through initial dilution in any outfall system. The conclusion drawn from these data was that regardless of degree of treatment there will be times when a surface effluent field in the Central Bay will deviate from background in apparent color and will therefore be visible. At this point representatives of the Department of Public Works initiated discussions with the staff of the Regional Water Quality Control Board to clarify the matter of whether a visible effluent field in the Central Bay would, per se, be judged to constitute a violation of requirements.

Discussions with the Regional Board were still at a preliminary stage when this report was written, but tentative agreement had been reached that a visible effluent field would not of itself be judged a violation, provided that the turbidity and true color of the effluent field did not deviate by more than a prescribed amount from background measurements. Implementation of this agreement requires selection of laboratory techniques for the evaluation of true color and the establishment of reasonable criteria for maximum allowable deviation from background. Techniques for measuring turbidity, of course, are in common use.

Turbidity is amenable to dilution in straight line ratio. Thus the present North Point effluent, with a turbidity of 52 JTU, would raise the background level by only 0.3 JTU if discharged at peak dry weather flow rate. For the lowest turbidity value measured in the Central Bay, 1.6 JTU, an increase of 0.3 units would be a 20 percent change. Assuming a lower turbidity value of 30, which is expected to be representative of the effluent after chemical treatment is initiated at North Point, the incremental increase would be only 0.17 JTU, or 11 percent. It does not appear reasonable to assume that an increase in turbidity of 0.3 JTU will be considered to constitute a violation of water quality criteria. The above analysis deals with dry weather flow only. It is assumed that during periods when wet weather flows are being discharged the background turbidity of the bay will be higher and the percentage increment of increase will not change.

True color is a major unknown in the analysis of outfall performance. Neither the background color of the bay nor the color of the present North Point effluent are known, nor has a method of measuring true color been accepted as a basis for enforcement. In its favor, however, can be stated the fact that true color can be measured by established and repeatable laboratory techniques. It is expected that true color will exhibit an approximate straight line ratio of decrease with dilution. In the absence of colored industrial wastes, a good quality of primary effluent diluted in excess of 100 to 1 should comply with any requirements which may be established for true color.

Dissolved Oxygen. Present values for dissolved oxygen in the Central Bay are not only well in excess of the 5.0 mg/l set in the present North Point discharge requirements, but are also in excess of the 90 percentile requirement of 6.5 mg/l proposed by the Bay-Delta Program. Initial dilution through the proposed outfall will be sufficient to prevent any local sag in dissolved oxygen. A study of summated surface current vectors, confirmed by surface drift studies, shows that an effluent field in the surface waters of the Central Bay moves rapidly seaward, passing out of the bay after an average residence time which is probably less than two days. Mathematical model studies performed in connection with the February, 1969 report on alternative methods of effluent disposal[3] showed that the maximum oxygen sag in the Central Bay due to all of San Francisco's discharges in the year 2000 would not exceed 0.07 mg/l at any place. There is no evidence to indicate that a degree of treatment higher than the present conventional primary treatment is necessary to maintain dissolved oxygen values at desired levels in the Central Bay.

Coliform Organisms. The City of San Francisco has demonstrated that it is possible to meet the coliform organism requirement in its present effluent. The submarine outfall line will provide about 30 minutes of chlorine mixing and contact time at maximum dry weather flow, which will be in addition to the contact times in the present plant facilities. Initial dilution will further reduce the coliforms in the plant effluent by more than 140 to 1. Construction of the submarine outfall will permit San Francisco to meet the present North Point coliform requirement while discharging primary effluent chlorinated sufficiently to achieve a 99 percent reduction of coliforms. This low rate of chlorination will meet the water quality objectives of either the Regional Board or the Bay-Delta Program.

Federal Requirements. In the process of meeting the discharge requirements as set forth above, all of the recently proposed requirements for federal grant eligibility, with one exception, will also be met. The one exception is the requirement that the plant must remove at least 85 percent of the 5-day BOD. However, the Commissioner may waive this requirement if discharge is into open ocean waters through an ocean outfall.

It is the contention of this report that with respect to its suitability for sewage disposal the Central Bay is at least as good, and probably better, than the average ocean disposal site. In support of this contention, attention is called to the following facts:

1. Currents are much stronger than in the open ocean, providing more effective initial dilution.
2. Dispersion coefficients (Fig. 4-42) are approximately one order of magnitude higher than the average of values reported in the literature for the open ocean. This means that subsequent dilution of a surface field will be considerably more rapid than would normally occur in the open ocean.
3. Net displacement in the surface layer is strongly seaward, indicating that no significant build-up of conservative pollutants will occur.
4. An average tidal exchange value of 20-30 x 10^9 cu ft/day injects massive amounts of new water into the Central Bay on each tidal cycle.

If the EPA is willing to accept this contention, as documented by the oceanographic data collected in the course of a year's study of the disposal area, there should be no problem in obtaining federal construction grants for facilities designed to discharge primary effluent to the Central Bay through a submarine outfall.

Summary of Treatment Requirements. With three possible exceptions, the recommended submarine outfall can meet all water quality objectives while discharging an effluent equivalent in quality to that now being discharged by the North Point plant. The three possible exceptions are turbidity, true color and the proposed federal regulation which would require secondary treatment for all discharges except to the "open ocean" as approved. It is expected that the inauguration of chemical treatment at the North Point plant will provide a reasonable factor of safety with respect to turbidity requirements. True color will remain a question mark until more is known than at present, but there is no reason to assume that either primary treatment alone or primary plus chemical treatment will not be adequate. With respect to the proposed federal regulation, it can only be stated that the documented results of the present study support the contention that the Central Bay is at least equal to the open ocean as a disposal site.

Wet Weather Outfalls

Wet weather design flow from the North Point zone is 350 mgd (Table 6-2). Of that amount, 200 mgd will be discharged through the dry weather outfall described previously. While no decision has yet been made regarding where wet weather treatment and discharge facilities will be located, there are only two basic options to be considered for the discharge of intermittent wet weather flows: either the intermittent wet weather flows will be discharged through the dry weather outfall, or they will be discharged through a separate outfall.

As discussed in Chapter 4 and presented in the oceanographic design criteria in Chapter 6, it is a basic premise of this report that environmental protection will be best achieved by discharging wet weather flows in a manner which will result in a surface effluent field. Seaward advection of the surface layer will then move the field out of the bay in the shortest possible time. Design in accordance with this premise, however, will require the approval of the regulatory agencies. Ultimately, the plan which must be followed is the one which meets the requirements of the Regional Water Quality Control Board. A surface field will have a low initial dilution and will not meet the Regional Board's present objectives for turbidity and color. If the Regional Board does no approve of the concept of rapid seaward advection in preference to rapid initial dilution for wet weather flows, wet weather outfalls must be designed for high initial dilution. Discharge of intermittent wet weather flows through the dry weather outfall will of necessity result in high initial dilution. If a separate outfall is constructed for wet weather flows, it may be designed either to produce a surface field or to achieve maximum initial dilution.

Combined Outfall. Only a cursory analysis is required to show that use of a single outfall to carry by gravity both the wet weather flow of 350 mgd and the present dry weather flow will create several unsatisfactory conditions. The outfall pipe would be larger than 10 ft in diameter, and the velocity at present peak dry weather flow would be less than 2 fps. To avoid an excessively long diffuser section the diffuser ports would have to be about 5-in diameter, which would give initial dilutions of less than 100 to 1 at peak flow. At flows less than average dry weather, the head loss across the large ports would be so small than uneven distribution would occur and results of initial dilution would be unpredictable. If a single outfall is to be used for both dry and wet weather flows from the North Point area, therefore, it should be planned on the basis of effluent pumping at the North Point plant.

The outfall and diffuser designed for the North Point plant can satisfactorily dispose of both the present dry weather flows and the future design flow of 200 mgd without effluent pumping. The same outfall, with a pumping head of 20 ft, can also satisfactorily convey and disperse the peak wet weather flow of 350 mgd. As shown in Fig. 7-2, the diffuser would provide initial dilutions in excess of 100 to 1 for the peak wet weather flow of 350 mgd.

Separate Outfalls. If a separate outfall is constructed for the discharge of intermittent wet weather flows, it will have a capacity of 150 mgd. The most appropriate and economical location will be determined on the basis of decisions yet to be made regarding the location of required wet weather conveyance, storage and treatment facilities. From a water quality standpoint the location of the second outfall is not of major importance. Dispersion characteristics and water quality are not substantially different for the entire waterfront area of the North Point zone. However, seaward displacement will be more rapid from stations closest to the Golden Gate, and the outfall should be located as far westerly as economics will permit. For greatest protection from damage by ships' anchors, the outfall should be located either west of Pier 37 or within the cable area which extends from Pier 9 to Pier 24. The westerly location again is preferable.

If the wet weather outfall is to be designed for maximum seaward displacement, the depth of water over the diffuser need only be sufficient for navigational purposes. For the dry weather outfall, this depth was set by the San Francisco Port Commission at 55 ft. The outfall must extend from shore far enough to entrain the effluent field in the main body of the westward-moving surface water mass. At most locations a length of 2500 ft should be sufficient. Depending on the head available, the outfall pipe diameter would probably be between 72 and 96 inches. In order to insure that the effluent will rise to the surface, the diffuser would be designed to produce an initial dilution of about 10 to 1. With greater initial dilution the effluent would reach stability with the stratified winter water mass at some point below the surface, and seaward advection would be impeded. The diffuser would have a small number (5 to 10) of large diameter ports spaced widely and discharging straight upward.

If the wet weather outfall is to be designed for maximum initial dilution, the same design parameters used for the dry weather outfall would be employed. In this case preference would be given to depth of water over the diffuser. Water depths of 70 ft or greater are generally available within 3000 ft of the shoreline all along the waterfront from Rincon Point to the marina.

Treatment Required for Wet Weather Flows. Intermittent wet weather flows will require treatment for substantially complete removal of gross settleable and floatable material, followed by disinfection. Whether or not additional treatment is required will depend on the Regional Board's attitude toward turbidity, discoloration and maximum initial dilution as opposed to maximum seaward advection. With maximum initial dilution chlorination will be required to achieve about a 99 percent reduction in coliforms. For maximum seaward advection a 99.9 percent coliform reduction will be necessary.

SOUTHEAST ZONE

The Southeast Water Pollution Control Plant has a submarine outfall and diffuser with a capacity of 70 mgd, equal to the hydraulic capacity of the treatment plant. A steady-state dye study of the outfall, reported in Chapter 4, showed that the diffuser achieves an initial dilution of 100 to 1 or better most of the time. Dilutions less than 1000 to 1 were not observed farther than about one mile from the diffuser. Because the Southeast zone has a functioning dry weather outfall, less attention was paid to the collection and analysis of oceanographic and ecological data for the bay south of the San Francisco Bay Bridge. As a result, recommendations for discharges in that area cannot be as specific as those for the Central Bay and the Gulf of the Farallones. Nevertheless, some general conclusions can be drawn from the information available.

South of the Bay Bridge the effect of tidal flushing is less than in the Central Bay. The further south one goes the less effective tidal flushing becomes. On the other hand, the shallows and shoreline areas south of Alameda and Hunters Point fall into the category defined by the ecological studies as requiring the highest dilutions for protection of the environment. It is not likely that the ecological design criteria can be met during prolonged periods of high wet weather flow from the Southeast zone. The criterion for 1000 to 1 dilution in shallows and shoreline areas was established for an effluent with a toxicity equivalent to the present dry weather discharge from the City of San Francisco's three primary treatment plants, and includes a 10 to 1 safety factor above the limit of detectable adverse change in the most sensitive organisms. The dilution criterion provides a useful yardstick for measuring the relative merits of different discharge locations and methods. In the case of the Southeast zone the available discharge sites must be classed as less desirable than those for the North Point and Richmond-Sunset zones. This does not mean that the discharge of 330 mgd of wet weather flow from the Southeast zone will cause any serious, or even any detectable ecological damage to the areas of concern. It does mean that if wet weather flow is determined to have a toxicity equivalent to dry weather flow, the safety factor protecting against adverse change will be reduced. Further evaluation of the toxicity of wet weather overflows, which was not investigated in this study, may indicate that there is no cause for concern in any event.

Net seaward advection of the surface layer in the bay waters adjacent to the Southeast zone is lower than in the Central Bay, but still has a component of several miles per tidal cycle at most locations. This net seaward advection is sufficient to make a significant reduction in residence time within the bay for those wastes discharged on the surface. Since there is an obvious advantage to maintaining the shortest possible residence time in the bay during the period when waste discharge to the bay is at a maximum, it is recommended that intermittent wet weather discharges to the bay from the Southeast zone be made through outfalls designed to produce a surface field.

As in the case of North Point zone, the basic treatment required for intermittent wet weather discharges from the Southeast zone will be substantially complete removal of settleable and floatable material plus chlorination. For maximum initial dilution a 99 percent reduction in coliforms will be necessary, and for maximum advection (surface field) a 99.9 percent reduction will be necessary. Additional treatment may be required by the Regional Water Quality Control Board, but the need is not indicated by this study. Any additional treatment which reduces the toxicity of the effluent will reduce correspondingly the necessary dilution of effluent in bay water.

RICHMOND-SUNSET ZONE

All of the inter-zone waste transfer plans under consideration by the San Francisco Department of Public Works involve transfer of wastes into the Richmond-Sunset zone for open ocean disposal. The Richmond-Sunset zone, therefore, has the greatest number of flow options which require specific consideration (Table 7-1). Each of the dry weather and wet weather flow options is considered separately below, including outfall size and location, performance and construction cost. Degree of treatment required is discussed for both dry and wet weather flow, and possible combinations of some of the options are considered. Table 7-2 summarizes design and cost figures for all options.

Available Discharge Sites

Water depth is the major controlling factor in the selection of potential discharge sites in the Gulf of the Farallones. Two separate factors, navigation and initial dilution, dictate that the water depth for a major outfall in the Gulf of the Farallones must be at least 40 ft. The Corps of Engineers, charged with protection of navigation in coastal waters, follows a general rule that the top of a submarine pipeline must be at least 7 ft below the bottom elevation of the navigable channel. For the South Bar area, minimum water depth is about 34 ft. Thus, the depth to the top of a submarine should normally be at least 41 ft for any pipeline installed south of Pt. Lobos. To allow clearance for the diffuser jets, the minimum water depth must be about 45 ft.

Initial dilution of effluent discharged from a diffuser is strongly influenced by water depth. Dilution obtainable increases rapidly with an increase in depth. Taking as a guide the Bay-Delta objective of a median dilution of 100 to 1, it is generally more desirable to construct an outfall to a depth greater than 40 ft than it is to try to achieve 100 to 1 dilution at a depth of 40 ft or less.

The oceanographic design criteria presented in Chapter 6 established one mile as the minimum desirable distance from shore for a major waste discharge, and the ecological criteria expressed preference for a site south of the centerline of the Golden Gate. A further practical restriction is that the outfall should not be constructed in or across the main shipping lane entering the Golden Gate. To summarize the basic criteria for a waste discharge site in the Gulf of the Farallones, it should be at least one mile from shore, south of the Golden Gate centerline, outside the main shipping lane and in a water depth of about 45 ft minimum. Referring to a chart of the Gulf of the Farallones (Fig. 7-4), it will be seen that the area which meets all of these criteria is distinctly limited. One suitable area lies inside the bar west of Point Lobos, and the second area lies in an arc outside the bar to the west and south.

Table 7-2 Cost Summary, Richmond-Sunset Zone Submarine Outfall Options

Outfall option	Discharge location	Design flow, mgd	Outfall dimensions		Project cost, million dollars
			Diameter, inches	Length, feet	
1	Inside bar	70	54	8000	4.5
2	South of bar	70	54	8-10,000	5.0-6.2
3	Inside bar	140	72	9800	7.0
4	Inside bar	340	102	7500-8500	11.3-12.3
4	Outside bar	340	114	22,000	28.7
5	Inside bar	255	84	2700	4.5
6	Inside bar	620	138	3400	11.7
7a	Inside bar	100	60	2500	3.1
7b	South of bar	520	132	9700	16.1

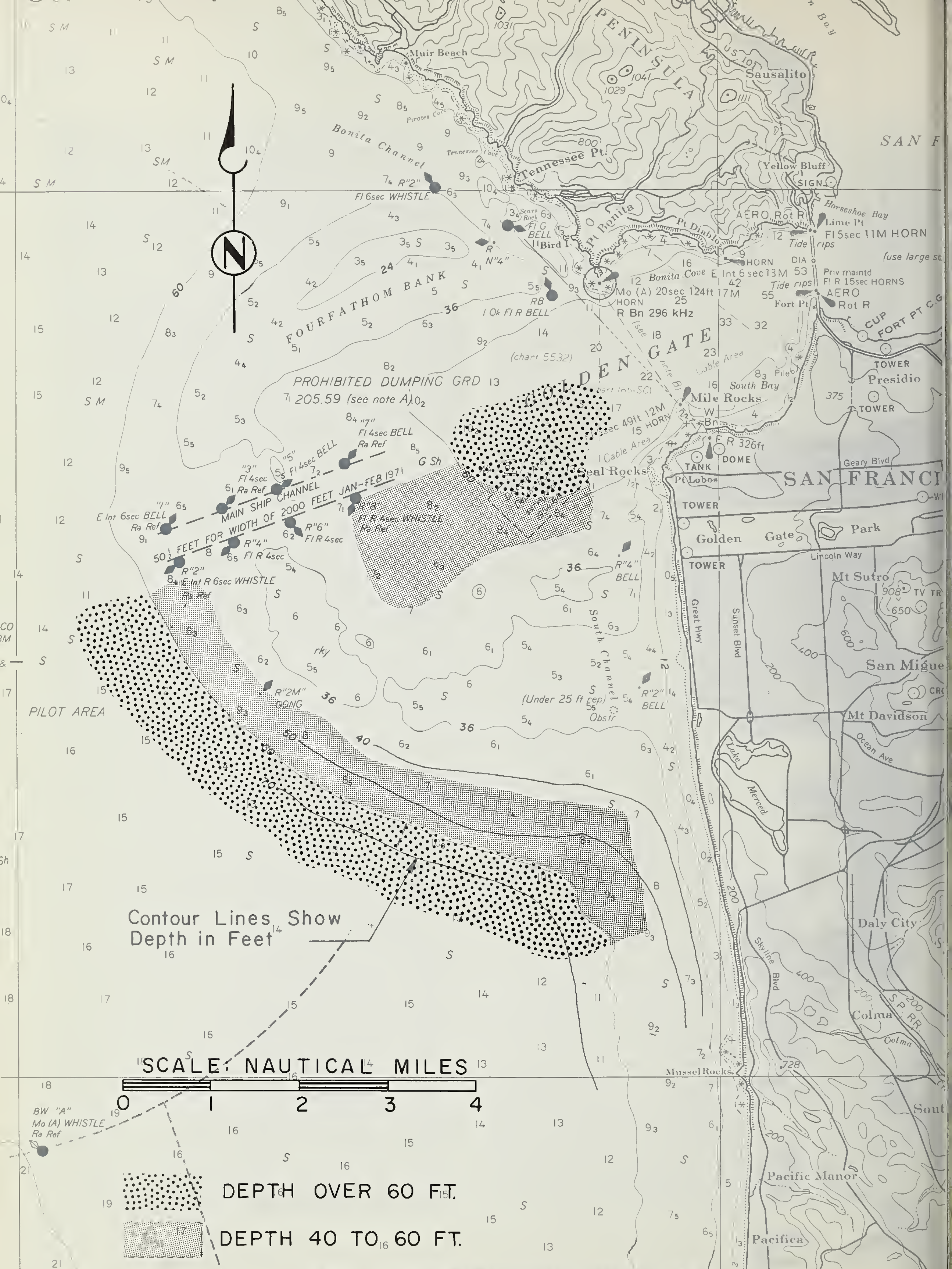


Fig 7-4 Suitable Waste Disposal Areas, Gulf of the

Dry Weather Disposal Option 1

The four dry weather disposal options presented in Table 7-1 and discussed below consider disposal to the Gulf of the Farallones of the peak rate of discharge from one, two or all three of the city's present water pollution control plants.

Under Option I the dry weather flow from the present Richmond-Sunset Water Pollution Control Plant, up to a peak rate of 70 mgd, would be discharged in the vicinity of Lands End. Two outfall sites were investigated, identified as Sites A and B on Fig. 7-5. Dilution was investigated at extreme low water, 1.8 ft below mean lower low water. Required head was evaluated at high water, 6.7 ft above MLLW. The analysis for initial dilution assumed a condition of low slack water and no density stratification. Under these conditions, which have been measured in the proposed disposal area in the summer and fall months, the effluent field will rise to the surface.

Site A, which represents the shortest and most direct route by which an outfall can be run to a suitable disposal area, was investigated first. A series of computer analyses of hydraulics and initial dilution showed that 100 to 1 dilution could not be obtained at 45 ft depth even at limiting values of port diameter, jet velocity and port spacing. Under these circumstances, if dilution is insufficient the diffuser must either be placed in deeper water or lengthened, adding more ports with a reduced velocity per port. For Site A, the additional length of diffuser required to achieve 100 to 1 initial dilution would cost as much as running the outfall to a greater depth with a shorter, more efficient diffuser. At this point the investigation of Site A was abandoned.

To reach deeper water, the diffuser was shifted northward toward the deep channel near the Golden Gate, to Site B (Fig. 7-5). At Site B, with a water depth of 60 ft, an initial dilution of about 110 to 1 can be achieved under the most adverse conditions of low slack water and peak flow rate of 70 mgd. Site B is recommended for dry weather disposal Option 1.

Outfall Design. The head available at the outlet end of the Richmond-Sunset Water Pollution Control Plant for discharge through a submarine outfall is 21 ft. However, it is recommended that 6 ft be reserved for losses involved in possible future expansion of the treatment process. For long-range planning, therefore, the available head is only 15 ft. A 69-in diameter pipeline would be required to convey and disperse the design flow with only 15 ft of head. However, a pipe that large would have velocities less than 2 fps even at present maximum daily flows, and self-cleaning velocities would occur only during wet weather flow conditions. This factor alone is enough to indicate the advisability of effluent pumping. Further points in favor of effluent pumping are the greater head available for transmission and discharge, which will permit use of a smaller pipe, shorter in length, discharging at a shallower depth. In view of these facts, effluent pumping was included in the preliminary design of the outfall from the Richmond-Sunset plant. A head loss curve for the recommended outfall is shown in Fig. 7-6.

The recommended outfall will consist of 8000 ft of 54-in. diameter reinforced concrete pipe, of which approximately 1300 ft will be located on land and 6700 ft under water. The outfall will terminate in a 540-ft diffuser section located one mile offshore in 60 ft of water. Diffuser ports will be 3-in. diameter spaced 6 ft apart on alternate sides of the pipe. Ports will be located approximately 9-in. above horizontal centerline of pipe and will be designed for a maximum velocity of 25 fps at the peak flow rate of 70 mgd. The outfall will be laid in a trench to about the beginning of the diffuser section. The diffuser section will be laid on the natural bottom or will be constructed on piles if necessary to insure its stability. A final decision on this matter will be based on design surveys of bottom conditions, but for the purposes of estimating construction costs it is assumed that the final 800 ft of the outfall will be constructed on piles.

Contract cost for the submarine portion of the outfall is estimated at $3.1 million, and total project cost at $4.5 million.

Outfall Performance. For the recommended outfall, initial dilution versus flow is shown in Fig. 7-6. Subsequent dilution due to horizontal dispersion at any time after release may be determined from Fig. 6-1, using an initial field width of 600 ft. Apparent dilution of coliform bacteria due to normal dieoff in sea water at any time after release may be determined from Fig. 3-2. At any time after discharge, therefore, the dilution of a conservative constituent at the most concentrated point in the effluent field may be determined by multiplying initial dilution by subsequent dilution. The apparent dilution of coliforms is determined by multiplying that product by the value determined from Fig. 3-2. This analysis is conservative

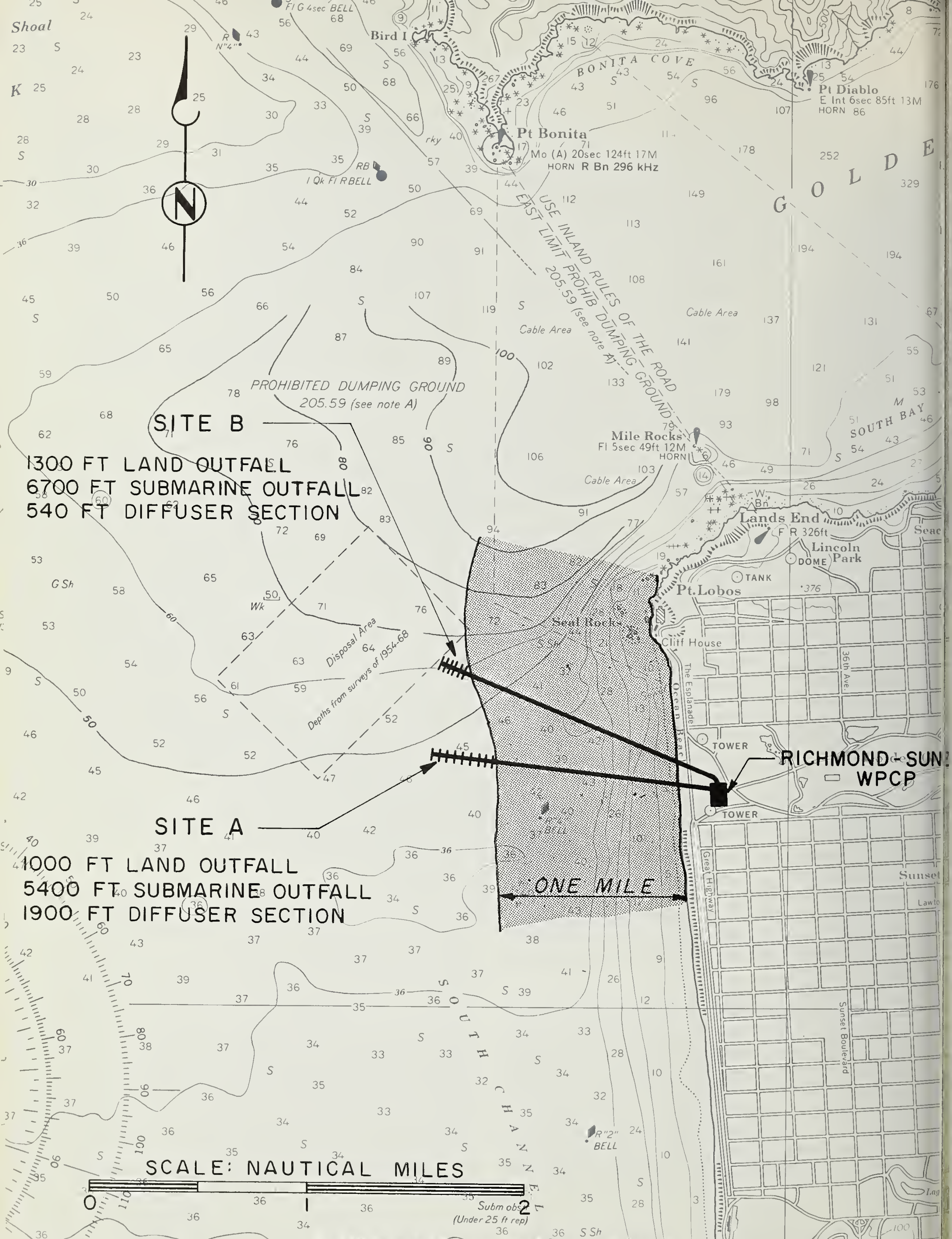


Fig. 7-5 Richmond-Sunset Zone, Dry Weather Disposal Option 1

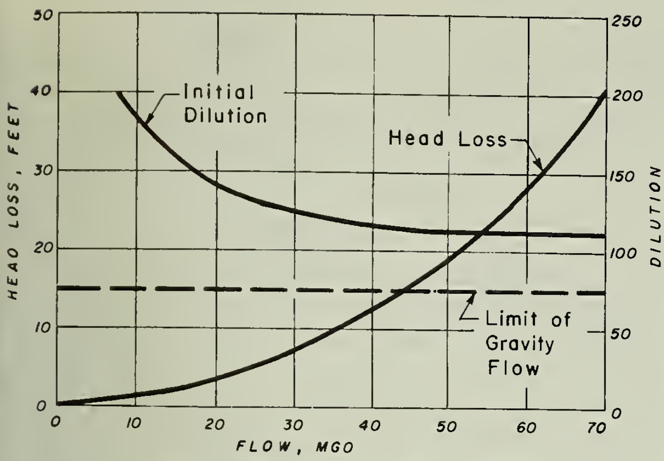


Fig. 7-6 Head Loss and Initial Dilution Characteristics, Richmond-Sunset Dry Weather Disposal Option 1, Site B

because it ignores dilution due to vertical dispersion, which provides yet another multiplier for total dilution.

The dilution objective for shallow water (less than 10 ft deep) and for shoreline areas was established by the ecological studies as 1000 to 1 for prolonged exposure (more than 24 hours at a time). For coastal areas, this objective would apply only to the shoreline. The oceanographic studies showed that the net advection from Site B will be strongly seaward, and that a surface effluent field will travel toward the shoreline for only a brief period during flood tide. Even during flood tide the effluent field will move toward the Golden Gate with the main water mass, and only the edges of the dispersing field will ever intersect the shoreline. A further safety factor is the fact that much of the time the effluent field will be submerged due to density stratification in the discharge area, and obviously only a surface field can affect the shoreline, which is at the water surface. This density stratification is strongest during a flood tide. However, let us assume that the effluent forms a surface field and moves shoreward at the fastest rate observed during the oceanographic studies, as shown on Fig. 4-19, which was a dry weather period. Initial dilution at future peak dry weather flow will be 120 to 1. After approximately 1-1/2 hrs the field will reach its closest point to the shoreline, and subsequent dilution in the center of the patch will be 3.4 to 1. Dilution at the diffused edge of the patch which may contact the shoreline will be at least 3 to 1 in relation to the center of the patch. Under these conditions, maximum concentration at the closest shoreline area would be about 1400 to 1, and this concentration would not persist for more than about eight hours per day.

The ecological investigations placed an objective for dilution of an effluent field at the ocean floor of 500 to 1, which again includes a 10 to 1 safety factor. The effluent field will reach the ocean floor only by rising to the surface or to a point of stability and then diffusing vertically to reach the bottom. The most critical point for bottom dilution will be the bar to the south and west of the discharge, because the bottom will be reached first in the shallowest area. At its shallowest point, the water depth over the bar is about 33 ft. The effluent field must travel about an hour on an ebbing tide at an average current speed of 1.3 K to reach the shallow area, and in that time dilution due to horizontal dispersion will be 2.2 to 1. The initial depth of field at a current speed of 1.3 K will be 9 ft, and the dilution due to vertical dispersion by the time the field reaches a depth of 33 ft will be 3.7 to 1. Multiplying the dilution factors for initial, horizontal and vertical dispersion gives a total dilution of 900 to 1, well in excess of the 500 to 1 recommended for protection of the benthos.

Dry Weather Disposal Option 2

Dry weather disposal Option No. 2 considers the possibility that the effluent from the Southeast Water Pollution Control Plant will be pumped across the San Francisco Peninsula and discharged to the Pacific Ocean in the vicinity of Lake Merced. Since the peak rate of flow from the Southeast plant is the same as for the Richmond-Sunset plant and the effluent has approximately the same characteristics, the discharge conditions and requirements are identical to Option 1 in all respects except location.

No specific location has been designated for the start of the submarine outfall for Option 2, and total length and cost are therefore nebulous at this time. However, the requirements can be defined within fairly narrow limits. An outfall designed as described for Option 1 with the diffuser located one mile offshore between the 50 and 60 ft depth contours (Fig. 7-7) will meet the criteria established in this report. Depending on the location of the shore terminus, the required length of the submarine section will be 8000 to 10,000 ft. Adequate head should be available from the initial pumping operation to permit the use of 54-in pipe. The problems of bottom stability which are likely to be encountered inside the bar should be totally absent outside the bar, and the diffuser section can

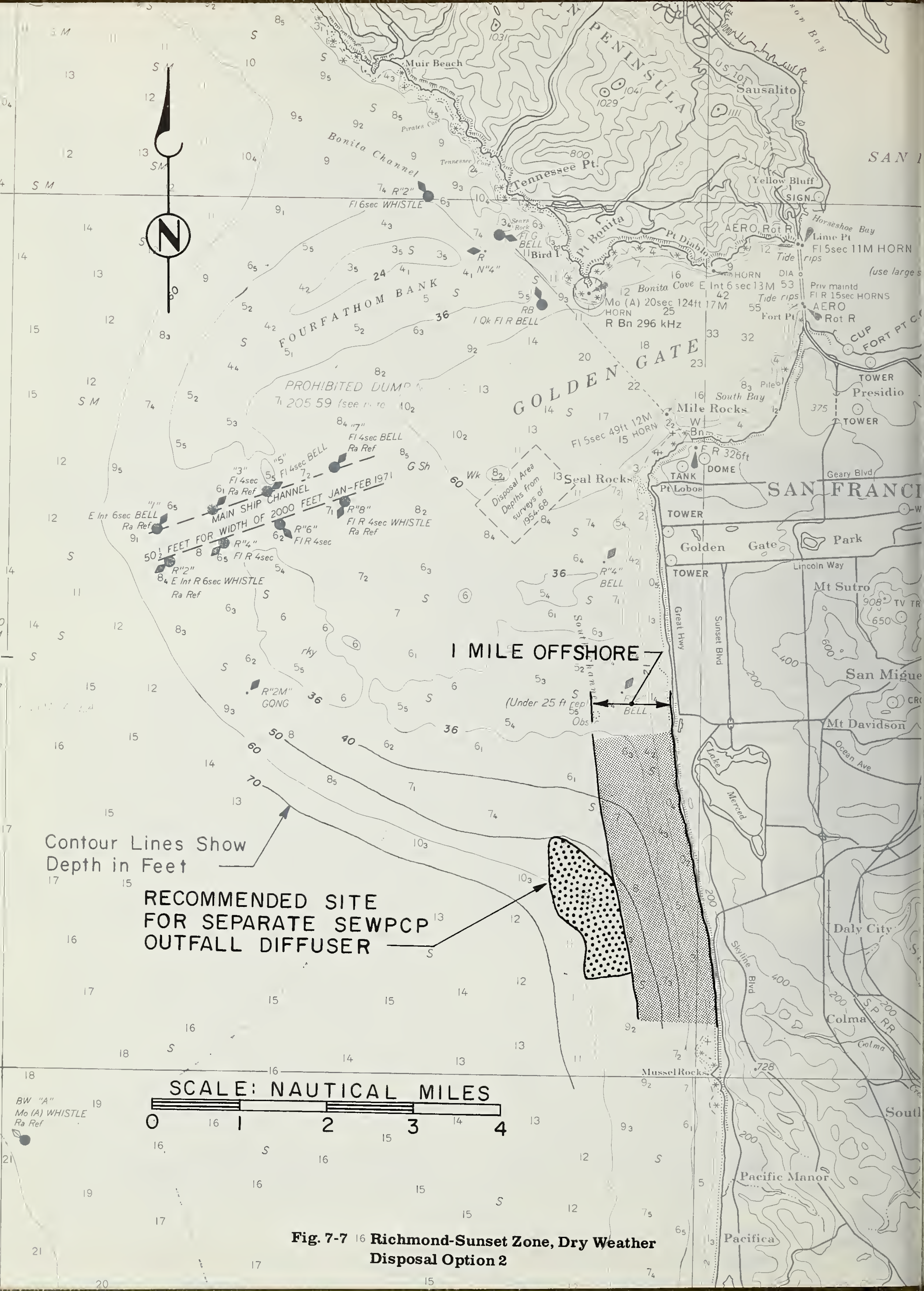


Fig. 7-7 Richmond-Sunset Zone, Dry Weather Disposal Option 2

be constructed directly on the natural bottom without pile supports. Contract cost for the submarine line is estimated at $3.4 to $4.3 million, depending on total length. Corresponding total project cost is $5.0 to $6.2 million.

Dry Weather Disposal Option 3

Option No. 3 considered the discharge of the effluent from both the Southeast and Richmond-Sunset Water Pollution Control Plants through a single outfall in the vicinity of Lands End. The peak rate flow from the two plants would be 140 mgd. The problems involved in disposal under Option 3 are again precisely the same problems discussed under Option 1. The larger flow for this option can be effectively dispersed by extending the outfall farther north into deeper water and lengthening the diffuser section. A moderate increase in initial dilution is desirable to compensate for the fact that the effluent field will be larger and will therefore disperse somewhat more slowly.

Outfall Design. The outfall recommended for dry weather Option 3 is shown in Fig. 7-8. Assuming that the outfall begins at the Richmond-Sunset Water Pollution Control Plant, it will consist of approximately 9800 ft of 72-in. pipe. Of that total 1500 ft will be installed on land and 8300 ft under water. The submarine section will terminate in an 800-ft diffuser section located one mile offshore in 75 ft of water. The diffuser will contain 134 3-1/2-in. ports spaced at 6 ft on opposite sides of the pipe. The last 1200 ft of the pipe, including the entire diffuser section, will be supported on piles for protection against shifting bottom conditions.

As shown in Fig. 7-8, the diffuser lies at the corner of an area designated for spoil disposal by the Corps of Engineers. Should this alternative proceed to final design, one of the first steps should be a petition for a change in boundaries of the spoil disposal area to prevent the possibility of dredged spoil being dumped on the diffuser section. If the boundary change cannot be obtained, the diffuser should be shifted northward outside the boundary of the disposal area.

The design assumes that effluent will be pumped from the Richmond-Sunset plant, but that the effluent from the Southeast plant will arrive at the shore terminus of the outfall with sufficient head for discharge by gravity. Contract cost of the submarine section of the outfall is estimated at $4.8 million, and total project cost at $7.0 million.

Outfall Performance. Curves for head loss and initial dilution for the recommended outfall are shown in Fig. 7-9. As the curve shows, initial dilution will be 130 to 1 at low slack water and no density gradient when the outfall is discharging its peak capacity of 140 mgd. At average current conditions initial dilution will be greater than shown. By extending the outfall into deeper water or lengthening the diffuser section even greater initial dilutions can be obtained. However, it is the purpose of this report to recommend the least costly installation which is deemed capable of satisfactory performance.

At an average current of 1.3 K the initial effluent field thickness will be 15 ft, and vertical diffusion will equal at least 2 to 1 by the time the field diffuses to the bottom. The time lapse before the effluent field will reach the shallow area of the bar on the ebbing tide will be about 1.3 hrs, and horizontal dispersion in that time will provide a dilution in excess of 2 to 1. The multiple of initial, horizontal and vertical dilution will again exceed the 500 to 1 recommended for protection of the benthos, even under this conservative set of assumptions.

Outfall performance with regard to protection of the shoreline will be the same as calculated for Option 1, with the calculation again indicating that the field in contact with the shoreline will be diluted in excess of 1000 to 1.

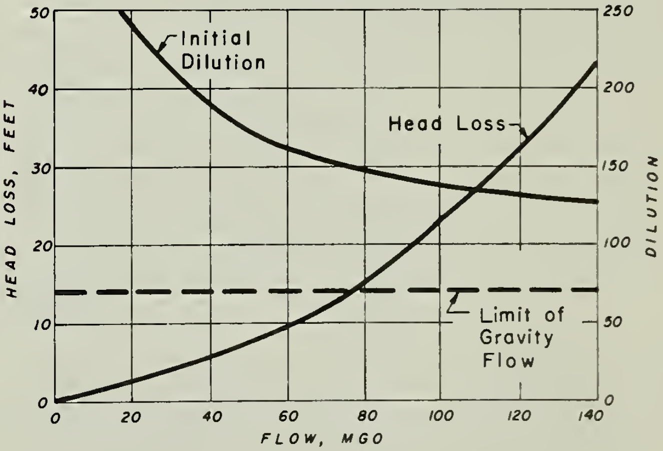


Fig. 7-9 **Head Loss and Initial Dilution Characteristics, Richmond-Sunset Dry Weather Disposal Option 3**

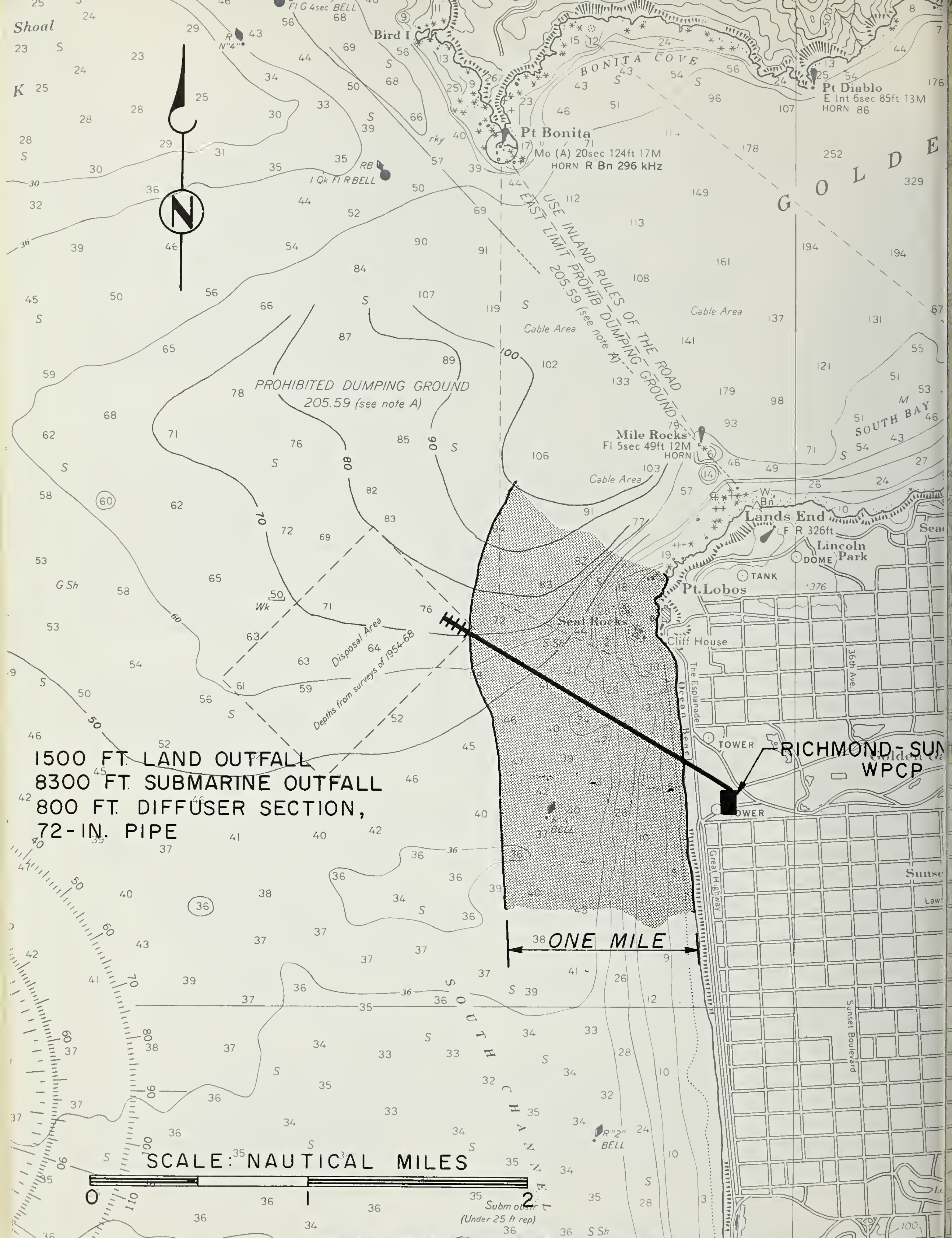


Fig. 7-8 **Richmond-Sunset Zone, Dry Weather Disposal Option 3**

Dry Weather Disposal Option 4

The final option to be considered for dry weather flows envisions the effluent from the entire city conducted to a single point of disposal. For this case effluent from both the North Point and Southeast Water Pollution Control Plants will be pumped across the San Francisco Peninsula and together with the effluent from the Richmond-Sunset plant discharged to the Gulf of the Farallones. The future average dry weather flow rate for this option is 125 mgd and the peak rate is 340 mgd, equivalent to the hydraulic capacity of all three plants. These flows place Option 4 in the classification of a major outfall, and it was concluded that disposal sites both inside and outside the bar should be investigated. The two sites, identified as Sites C and D, are shown on Figs. 7-10 and 7-11.

Outfall Design, Site C. As with the other dry weather options for the Richmond-Sunset zone, Option 4 assumes that head will be provided by pumping as required for optimum design of the outfall and diffuser. Depending on where the shore terminus lies, the submarine outfall for Site C will consist of 7500 to 8500 ft of 102-in. pipe, including a 1480-ft diffuser section at a depth of 95 ft. Site C represents approximately limiting conditions for an outfall in the Lands End area. To extend an outfall to a greater depth would require construction within the main channel of the Golden Gate, where the bottom is rocky and construction conditions extremely precarious. The diffuser section is slightly less than a mile offshore, but any further extension will intrude into the main shipping lane.

The diffuser for Site C will consist of 248 4-in. diameter jets at 6 ft intervals on opposite sides of the pipe. The last 4500 ft of the submarine line, including the entire diffuser section, will be constructed on piles for protection from unstable bottom conditions. Depending on length, the contract cost for an outfall to Site C will be $7.8 to $8.5 million, and the total project cost $11.3 to $12.3 million.

Outfall Performance, Site C. Head loss and dilution curves for Site C are shown in Fig. 7-12. For the assumed conditions of low slack water and no density gradient initial dilution will be 125 to 1 at peak flow and 160 to 1 at future average dry weather flow. The depth of the effluent field at peak flow and average current will be about 21 ft, but the field will be released at a point where it will be entrained in the main water mass moving westward on the ebb and toward the centerline of the Golden Gate on the flood.

Flowing westward at average ebb current, it will take the effluent field about two hours to reach a water depth of 40 ft. In that time horizontal dispersion will provide a dilution of 2.3 to 1, and dilution due to vertical dispersion will reach 2 to 1 before the benthos are affected. The overall dilution protecting the benthos will therefore be well in excess of 500 to 1.

During the summer and fall season when seaward surface advection is at a minimum there is some chance that a flooding tide will carry the effluent into brief contact with the shoreline along the Presidio. The number and duration of occurrences will be limited for the same reasons given in discussing Option 1, but the size of the effluent field may result in some contacts occurring at dilutions between 500 and 1000 to 1. Selection for Site C for Option 4 may therefore result in reduction of the ecological safety factor from 10 to 1 to about 5 to 1 for a few hours a day under certain oceanographic conditions in the summer and fall months.

Outfall Design, Site D. For a waste flow of the quantity considered under Option 4, the diffuser should be installed at a depth of at least 80 ft. Based on the oceanographic measurements taken in connection with this study it appears that an effluent discharged through a proper diffuser in 80 ft or more of water outside the bar will remain submerged at all times.

The shortest route to 80 ft of water outside the bar is Site D, shown in Fig. 7-11. An outfall to reach Site D will consist of 22,000 ft of 114-in. pipe, including a 1960-ft diffuser section. The diffuser section will contain 324 3-1/2-in. ports spaced at 6 ft intervals on opposite sides of the pipe. The pipeline route affords stable soil conditions throughout, and the entire line may be trenched into or laid directly on the bottom. Contract cost for a submarine outfall to Site D is estimated at $19.8 million and total project cost at $28.7 million.

Outfall Performance, Site D. Curves of head loss and dilution for a submarine diffuser at Site D are shown in Fig. 7-13. As the curve shows, the longer pipeline results in higher head loss than for Site C. The curve for dilution shows that at peak flow an initial dilution of 107 to 1 will be attained by the time the rising waste plume reaches stabi-

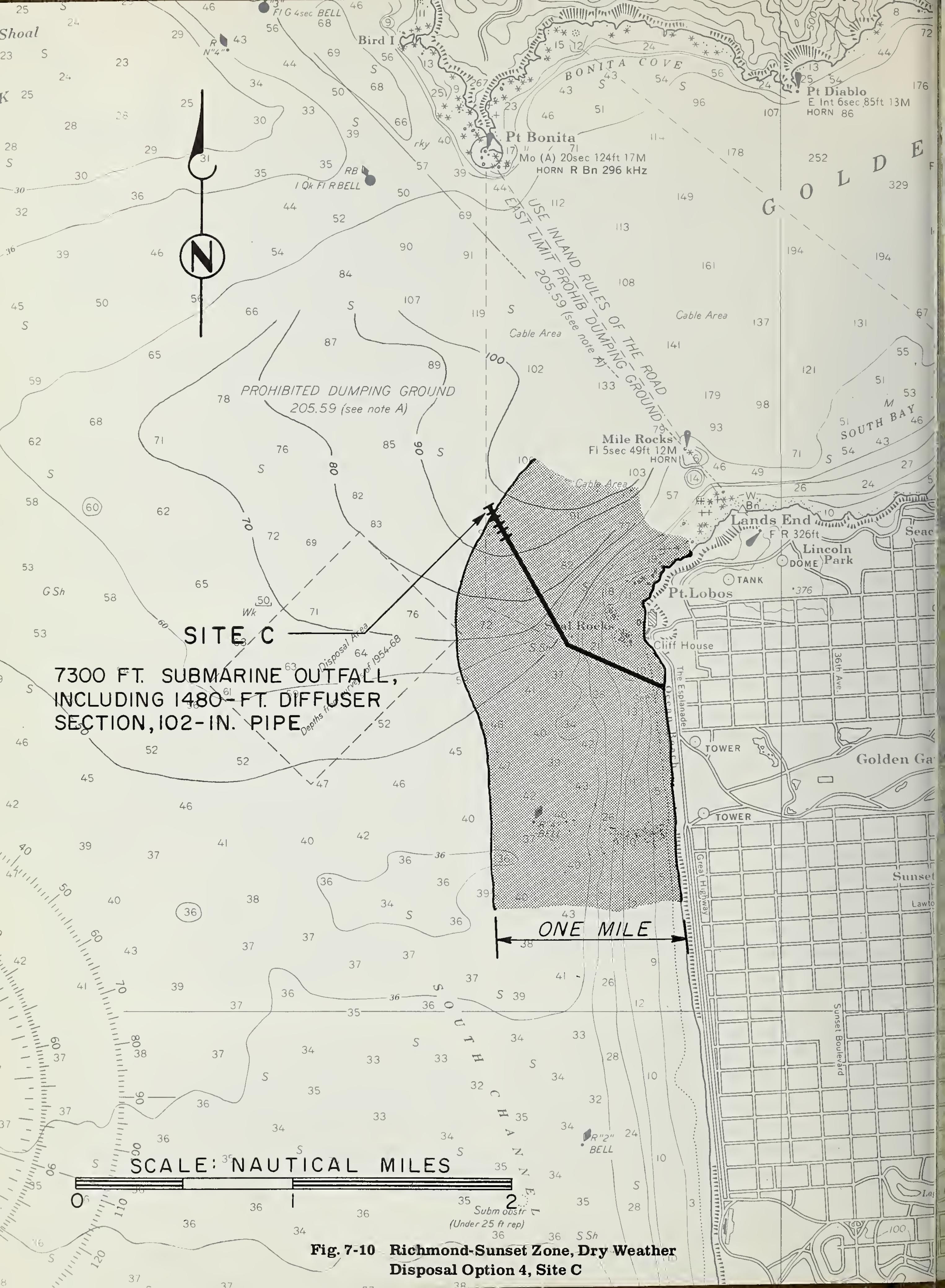


Fig. 7-10 Richmond-Sunset Zone, Dry Weather Disposal Option 4, Site C

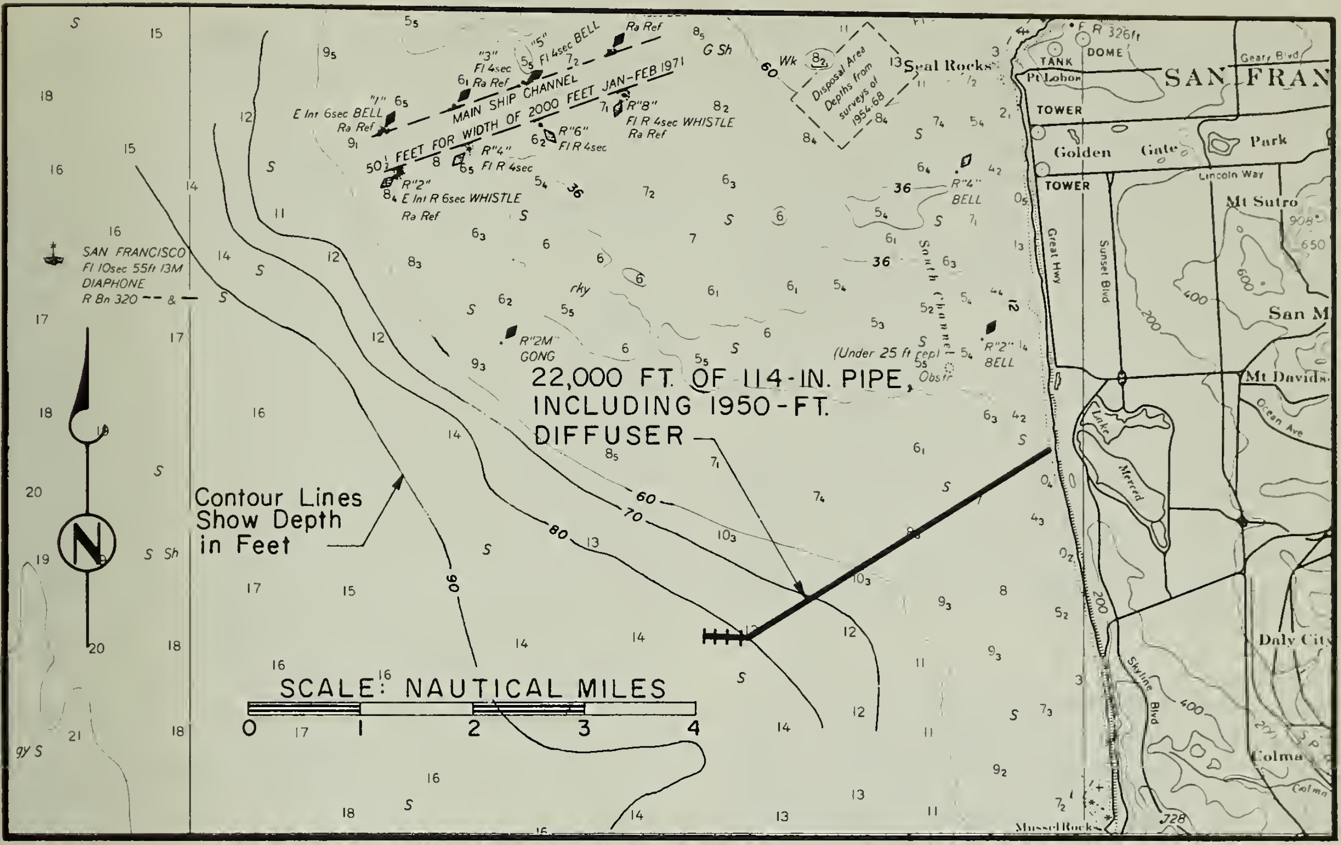


Fig. 7-11 Richmond-Sunset Zone, Dry Weather Disposal Option 4, Site D

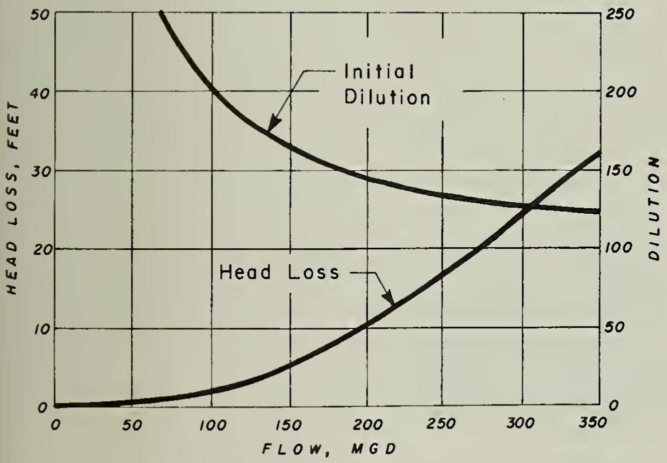


Fig. 7-12 Head Loss and Initial Dilution Characteristics, Richmond-Sunset Dry Weather Option 4, Site C

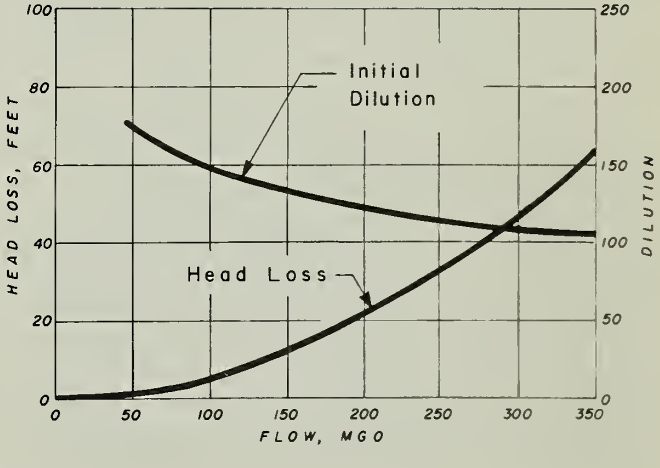


Fig. 7-13 Head Loss and Initial Dilution Characteristics, Richmond-Sunset Dry Weather Option 4, Site D

lity as a submerged field. It is anticipated that the waste field will reach initial stability at a depth of 15 to 30 ft under most conditions of waste flow and receiving water stratification. Because the total number of observations outside the bar is somewhat limited, however, it is possible that conditions will occasionally occur which will permit the effluent field to surface. Surfacing of the effluent field has no ecological significance, since the ecological criteria can be met in either case. Since the diffuser will be located over three miles offshore, it is not likely that the regulatory agencies will attach any esthetic significance to occasional surfacing of the effluent field.

All of the oceanographic information available on the Gulf of the Farallones outside the bar indicates that an effluent field from Site D will not contact either the shoreline or the benthos except in dilutions far greater than the recommended ecological design criteria.

Treatment Required for Dry Weather Flow

The ecological design criteria which were presented in Chapter 6 were developed in major part from laboratory tests on present San Francisco treatment plant effluents and from field evaluation of the impact of the present effluents on the marine enivronment. So long as these ecological design criteria are met, no improvement in the present degree of treatment is necessary for protection of the marine ecosystem. The analyses presented previously for dry weather flow options in the Richmond-Sunset zone indicate that all of these criteria can be met substantially all of the time at all of the sites investigated, and that chlorinated primary effluent is satisfactory from an ecological standpoint. If additional treatment is required, it will be because the regulatory agencies require it for reasons other than protection of the marine environment.

No recent discharge requirements have been established for the Richmond-Sunset Water Pollution Control Plant, and there is no clear indication at this time of the requirements which will be established for proposed discharges from the Richmond-Sunset zone. The degree of treatment required was evaluated, therefore, in relation to the policy objectives which have been established by the Regional Board and by the Bay-Delta Program.

Floatable and Settleable Material. All agencies require substantially complete removal of settleable material, which can be achieved by efficient primary treatment. The Bay-Delta Program objective of 55-65 percent removal of suspended solids can also be met by efficient primary treatment.

The analysis for floatable materials in the vicinity of the discharge which was presented in the interim report for the North Point outfall is also valid for the Richmond-Sunset outfall. That analysis indicated that floatables may approach, but will not exceed, the Bay-Delta objective of 20 mg/sq m in the surface field. The analysis of floatables accumulation on the beaches, presented in Chapter 4, showed that floatables released to the Gulf of the Farallones may be expected to accumulate along the shoreline south of the Golden Gate at a rate of 1.6 percent of the total mass emission per mile of shoreline. By making several assumptions, it was possible to check the accumulation of floatables per square meter of shoreline area. The assumptions were:

1. The Bay-Delta assumption of 30-day degradation of floatables will apply.
2. Degradation will be a straight-line function. This is probably conservative.
3. The mass emission of floatables after primary treatment will be 2 mg/l, or 340 lb/day for present average dry weather flow from the Richmond-Sunset plant.
4. The floatables will accumulate over a stretch of beach 20 m wide.

From these assumptions it was calculated that the accumulation of floatables on the shoreline from the Richmond-Sunset plant alone would be 1.1 g/sq m. The Bay-Delta objective is stated as 0.3 g/sq m from *all* discharges. This indicates a discrepancy of some two orders of magnitude between the Bay-Delta objective and present performance with regard to floatables. Such a discrepancy suggests that the test procedures for floatables, the assumptions listed above, the Bay-Delta objective for floatables or more than one of these in unrealistic. However, until this matter can be resolved by further investigation and translated into reasonable waste discharge requirements, treatment plants for discharge to the Gulf of the Farallones should make provision for the future installation of an efficient process for the removal of floatable materials.

Coliform Organisms. All of the proposed outfalls will provide a chlorine contact time in the outfall which is sufficient for good disinfection. The present objective of the Regional Board is a median MPN of 240/100 ml within 1000 ft of extreme low water. The objective of the Bay-Delta

Program is 1000/100 ml in 80 percent of the samples at any point within a mile of the shoreline. The latter objective, which is of course the most severe, can be met for any discharge option by achieving a 99 percent coliform kill in the plant effluent. This end is attainable at a fairly low chlorine dosage. For Option 4, Site D, outside the bar and over three miles offshore, chlorination will probably not be required at all.

Dissolved Oxygen. Because of the rapid dispersion of the effluent field, none of the options considered will perceptibly change the background value for dissolved oxygen. The present background value exceeds the Regional Board policy objective of 6.0 mg/l for a mean annual value and will meet the Bay Delta objective of 80 percent of background level in the mixing zone. Though the method for computing the median may need further definition, it also appears that dissolved oxygen in the surface waters inside the bar will comply with the objective of 85 percent of saturation as a median value which was set forth in the Preliminary Interim Water Quality Management Plan. Dissolved oxygen values in the surface waters outside the bar exceed all requirements at all times. In any event, failure to meet the objective for dissolved oxygen will result from low DO in the background water mass rather than a depression resulting from any of the dry weather discharges considered above.

Temperature, Turbidity and Apparent Color. The analysis of these parameters as presented for the North Point outfall is equally applicable to discharges to the Gulf of the Farallones. At certain times of the year a surface field will be visible in the receiving water regardless of degree of treatment afforded the waste. However, in each case the effluent field will surface more than a mile offshore, and during the season of greatest ocean water clarity will receive an initial dilution in excess of 100 to 1. There is no reason to believe that the water quality objectives set forth by the Regional Board would be violated by the discharge of primary effluent. During the period of maximum surface water temperatures a thermocline exists in the discharge area, and the surfacing effluent field will normally be colder than the surface waters.

Summary of Treatment Requirements. None of the conventional, well defined water quality criteria will be violated by discharge to the Gulf of the Farallones of an effluent equivalent to the present chlorinated primary effluent. No further improvement in treatment is necessary to protect the marine environment. However, further definition of the criteria for floatables, turbidity and true color may result in discharge requirements which will require further treatment in these areas. Long-range planning for ocean discharge of dry weather flows should therefore include contingent plans for the improved removal of floatables and suspended solids.

As a general rule, improvements in the degree of treatment will result in the reduction of both the esthetically undesirable aspects and the toxicity of the waste discharge. With a sufficiently high degree of treatment, the waste would be theoretically suitable for direct discharge to the ocean at the shoreline. As a practical matter, however, the public would probably object to a direct discharge at the ocean shoreline regardless of effluent quality, and a short outfall will always be required.

For a minimum outfall, which might be about 1500 ft long terminating in 20 ft of water, the waste stream would probably require treatment to remove virtually all suspended and floatable solids and to produce a high degree of disinfection and a 90 percent survival of test fishes in the undiluted waste stream. This would require complete treatment, including some form of tertiary treatment process such as activated carbon adsorption or rapid sand filtration. The subject of type and cost of treatment processes necessary to achieve various degrees of improvement in effluent quality is covered in detail in a separate study by Brown and Caldwell described in Chapter 1.

Wet Weather Flow Options

The disposal of wet weather flows for the Richmond-Sunset zone involves several special considerations. Basically, these all relate to the range and magnitude of wet weather flows being considered. In order to achieve both good performance at minimum flow and reasonable head loss at high flow a submarine outfall and diffuser is limited to a flow range of about 10 to 1. With special design provisions this range may be broadened slightly, but most of the wet weather options for the Richmond-Sunset zone are for flows too large to be included in the same outfall with the dry weather flow. Each wet weather option is therefore considered independently, and possible combinations are discussed in a later section.

The oceanographic data for the Gulf of the Farallones show a massive seaward component of surface advection during the wet weather period. The phenomenon is strongest when the delta outflow is the highest and the receiving water is most strongly stratified, but persists around the mouth of the Golden Gate all year. As explained in discussions of wet weather flow from the North Point and Southeast zones, it is a basic premise of this report that large wet weather flows can best be dispersed by discharging them into the seaward-moving surface layer. This will serve the following purposes:

1. Large wet weather flows will be rapidly advected seaward and away from the ecologically sensitive shoreline areas. During the height of the rainy season surface flow through the Golden Gate is continuously seaward.
2. The large wet weather flows will be entrained in the low-density surface layer and will be slow to diffuse vertically. This factor will give additional protection to the benthos.
3. Wet weather flow will be dispersed in a different regime and will not compete with the dry weather discharges for dilution capacity. The dry weather discharges, which must receive high initial dilution, will not rise to the surface during the stratified flow conditions which normally accompany large wet weather discharges.

It is true that, inevitably, the runoff from San Francisco's first storm or two of the season will occur during dry weather conditions in the Gulf of the Farallones. The first storm or two will therefore create a highly visible effluent field which will be displaced seaward, though not as rapidly as runoff during the height of the rainy season. However, the stratified flow regime will build up within a few days after the start of heavy and prolonged rainfall, which produces the discharge conditions of principal concern, and with the increased flow stratification will come higher background turbidities in the receiving water and increased net seaward advection.

To achieve the objective of a surface field with wet weather discharges, outfalls must be deliberately designed for low initial dilution. Inside the bar, for example, a wet weather discharge will not rise to the surface if it receives initial dilution greater than about 10 to 1. This indicates that diffusers for large wet weather flows should have a small number of large diameter, widely spaced diffuser ports.

Wet Weather Disposal Option 5

Flow option 5 for the Richmond-Sunset zone considers only those flows generated within the zone. Of the design wet weather flow of 325 for the zone, 70 mgd will be treated in the Richmond-Sunset Water Pollution Control Plant and discharged through the dry weather outfall. The remaining 255 mgd represents intermittent wet weather flow to be discharged through a wet weather outfall in the vicinity of Lands End.

The intermittent wet weather flow in this case is small enough to permit discharge through a conventional diffuser with high initial dilution in the event that the regulatory agencies do not approve of the concept of a surface field for maximum seaward advection. A conventional diffuser should not be considered, however, if a major dry weather discharge is to be constructed in the same area.

Outfall Design. Wet weather outfalls in the vicinity of Lands End are all planned on the assumption that the present trunk sewer to Lands End will be used to convey intermittent wet weather flows. Pumping will be required in all cases to generate the head required for discharge through the outfall.

For maximum seaward advection an outfall need be only long enough to release the effluent in the main flow stream through the Golden Gate. An outfall 2000 ft long extending to the beginning of a diffuser section at a depth of about 100 ft will accomplish this objective. Using for density structure of the receiving water the average of conditions on the ebb and flood tides as measured on February 24, 1970, it was calculated that the discharge will not reach the surface if initial dilution exceeds about 10 to 1. The problem then becomes one of attaining dispersion of the effluent field in the minimum length of time to avoid damage to plankton and fish populations. Referring to Fig. 6-1, it can be seen that a small field disperses laterally much faster than a large field. Thus, after one hour an effluent field with an initial width of 50 ft will be diluted 12 to 1, while a 500 ft field will be diluted only about 2-1/2 to 1 in the same time. This principle, translated into diffuser design, dictates the use of a small number of large diffuser ports widely spaced to produce several discrete small effluent fields which will diffuse rapidly.

The outfall for Option 5 will consist of 2700 ft of 84-in. pipe constructed northward from the

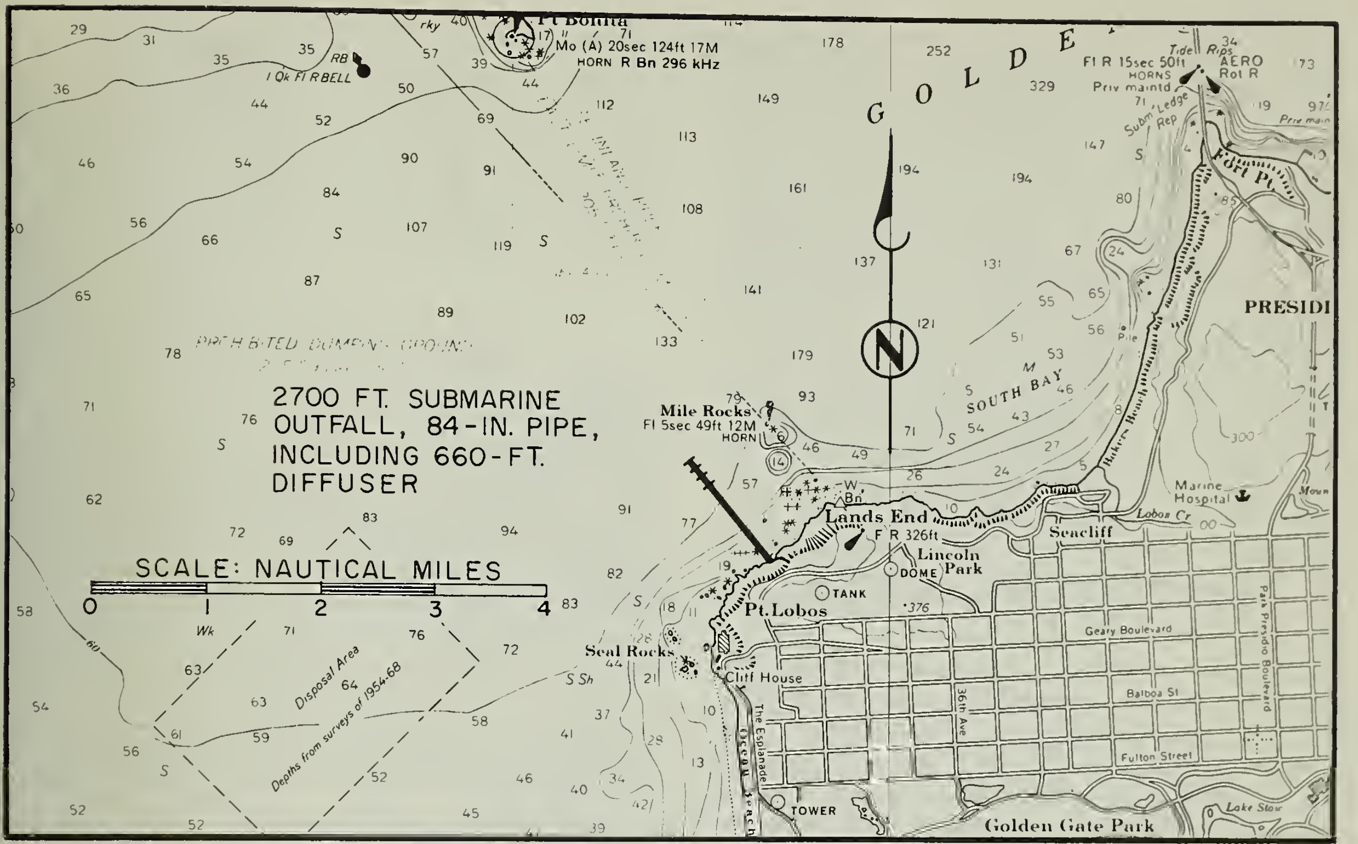


Fig. 7-14 Richmond-Sunset Zone, Wet Weather Disposal Option 5

present Lands End sewer outlet as shown in Fig. 7-14. The diffuser will consist of four 33-in. diffuser ports spaced at 230 ft intervals and discharging straight upward. The inlet of each diffuser port or nozzle will be at the bottom of the 84-in. pipe. This arrangement will keep the outfall filled with low-density, low-salinity effluent to discourage the growth of marine organisms which might otherwise clog or diminish the diameter of the outfall during the periods between intermittent overflow.

Because of the swift currents in the area of the outfall the entire outfall and diffuser will be constructed on piles. Because of the difficulty of access to the construction site and the probability that rock will be encountered along at least a portion of the route, the contract cost was estimated at 20 percent above the normal figure for a pile-supported outfall. On this basis the contract cost for Option 5 was estimated at $3.1 million, and the total project cost at $4.5 million.

Outfall Performance. The jets from the four diffuser ports will reach the surface with an initial dilution of 10 to 1 and a field width of about 40 ft each. In 25 minutes the individual fields will merge forming a single field with a width of about 950 ft. By this time total dilution will be 50 to 1. In another 75 minutes the large field will be diluted 2 to 1, giving a total field dilution of 100 to 1 after an hour and 40 minutes. This analysis ignores vertical dispersion, which is expected to be limited because of stratified flow.

The ecological criterion for surface dilution states that dilutions less than 100 to 1 should not be allowed to persist more than 24 hours. It will be recalled that this criterion contains a safety factor of 10. A further major safety factor in this case is the uniqueness of the exposure. Free-floating larvae and other planktonic forms may pass through the effluent field once, in which case they will be exposed to dilutions less than 100 to 1 for a maximum of one hour and 40 minutes. The nature of the circulation pattern, which displaces the surface layer continuously seaward, assures that these same organisms will never be exposed to the effluent field again except by remote coincidence. Uniqueness of exposure does not apply to

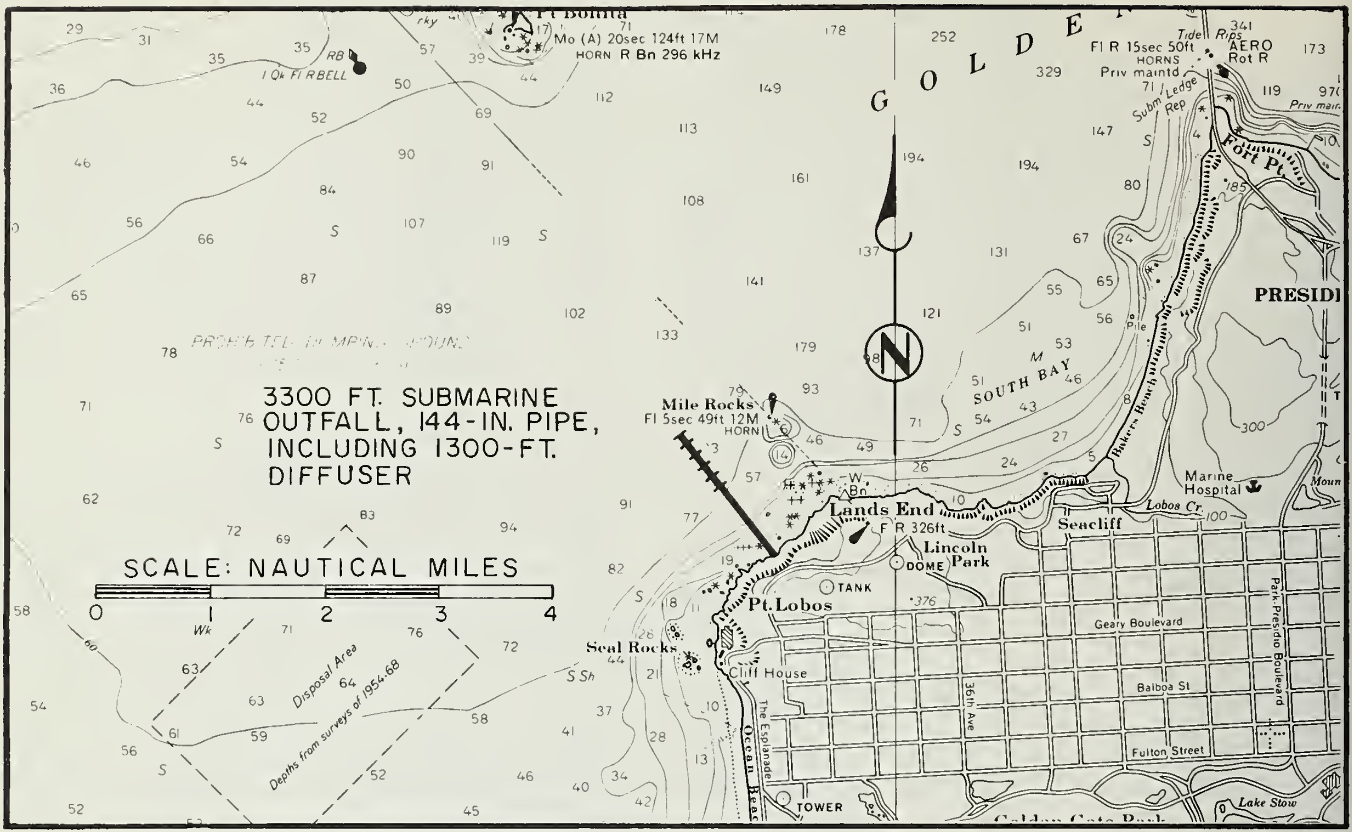


Fig. 7-15 Richmond-Sunset Zone, Wet Weather Disposal Option 6

the benthos or to the shoreline organisms, which remain fixed and subject to the same exposure again and again. This is considered a strong ecological argument in favor of the concept of maximum seaward displacement for large wet weather flows.

As was pointed out earlier, the surface field with a minimum initial dilution of only 10 to 1 will be clearly visible most of the time while an intermittent discharge is in progress. If the Regional Water Quality Control Board chooses to rule against field visibility, the outfall will have to be designed for high initial dilution to achieve a submerged field.

Wet Weather Disposal Option 6

Option 6 envisions the transfer of a major portion of the intermittent wet weather flow from the other two zones to the Richmond-Sunset zone, where it would be discharged at Lands End. The capacity of the wet weather outfall in this case will be 620 mgd. This flow is judged too large for effective dispersal inside the bar by maximum initial dilution, and maximum seaward displacement is recommended as the only alternative. The principles involved are the same as those set forth above for Option 5.

Outfall Design. The submarine outfall for Option 6 will be 138 inches, or 11.5 ft, in diameter. Total length, including a 1400-ft diffuser section, will be 3400 ft (Fig. 7-15). The diffuser will consist of seven 36-in. jets spaced 230 ft apart and discharging straight upward. The port inlets will be at the bottom of the pipe as described for Option 5. Also as described in Option 5, the entire pipeline will be supported on piles, and an extra allowance of 20 percent in construction cost is made because of difficult rocky terrain. Estimated contract cost is $7.3 million, and total project cost is $11.7 million.

Outfall Performance. The initial performance of the diffuser for Option 6 will be the same as described for Option 5. The discrete jets will reach the surface with an initial dilution of approximately 10 to 1 and will merge to form a single surface field after 25 minutes. At that time dilution will be 50 to 1. Because the combined field will be larger than Option 5, lateral diffusion will be somewhat slower. A 2 to 1 dilution of the combined field will require 95 minutes, and the total time required to reach a dilution of 100 to 1 will be two hours. Again, the analysis ignores vertical dispersion.

Wet Weather Disposal Option 7

Under Option 7 most of the intermittent wet weather flow from the North Point and Southeast zones will be transferred to the Richmond-Sunset zone and discharged in the vicinity of Lake Merced. Of the total wet weather flow of 620 mgd it is anticipated that 520 mgd (Option 7b) will be conveyed to the Lake Merced disposal point. The remaining 100 mgd, (Option 7a) representing runoff from within the Richmond-Sunset zone, will be discharged in the vicinity of Lands End.

Option 7A, Outfall Design. As with other intermittent wet weather discharges in the vicinity of Lands End, it is anticipated that the outfall for Option 7a will begin at the end of the present Lands End trunk sewer. The relatively small flow, 100 mgd, is amenable to dispersion by either maximum initial dilution or maximum seaward advection. The decision on which to use may depend on the quantity of dry weather flow which is to be disposed of in the same area. If 340 mgd of dry weather flow is to be dispersed in the same area by maximum initial dilution as described for Option 4, it is recommended that maximum seaward advection be adopted for Option 7a. In other cases either method of dispersion would be acceptable.

The outfall for either maximum initial dilution or maximum seaward advection will consist of 2500 ft of 60-in. pipe terminating at a depth of about 100 ft. Outfall location will be the same as for Option 5 (Fig. 7-14). In the former case the diffuser will consist of 73 4-in. ports spaced at 6 ft on opposite sides of the pipe, for a total diffuser length of 440 ft. For maximum seaward advection the flow would be discharged directly from the open end of the 60-in. pipe. The pipe will be built entirely on piles, and an allowance of 20 percent is included in the cost estimates for difficult and rocky terrain. For either alternative the contract cost is estimated at $2.2 million, and the total project cost at $3.1 million.

Option 7a, Outfall Performance. Initial dilution through the diffuser recommended for maximum dilution will be 125 to 1 at the peak flow rate of 100 mgd. Since discharges will occur only during wet weather, density stratification in the receiving water is virtually assured. Under this condition the effluent field will remain continuously submerged. The analyses for dry weather discharges of the same and larger magnitudes showed that no ecological damage will result from a 100-mgd submerged effluent field.

For maximum seaward advection the flow will simply be discharged through the open end of the 60-in. outfall pipe, creating a single jet which will achieve a dilution of about 10 to 1 at the surface. Field width at the point of surfacing will be 100 ft. Referring to Fig. 6-1, a surface field 100 ft wide will be diluted 10 to 1 in an hour and 20 minutes, which represents the maximum time that any organism could be exposed to dilutions less than 100 to 1.

Option 7b, Outfall Design. Plans for discharge of 520 mgd in the vicinity of Lake Merced are based on maximum surface advection. To achieve adequate dispersion of that quantity of waste by initial dilution would require an outfall extending some 20,000 ft offshore to a depth of 80 ft or more and discharging through a diffuser 2500 ft long. Dispersion by surface advection requires only that the waste be conducted about a mile offshore. As a practical matter, construction of a pipeline of the required size without obstructing navigation will require that the diffuser be installed in about 50 ft of water. To reach that depth in the vicinity of Lake Merced the diffuser must be about 1-1/2 miles offshore.

Assuming that the outfall has its shore terminus immediately west of Lake Merced (Fig. 7-16), the outfall will consist of 9700 ft of 132-in. (11 ft) diameter pipe, including an 1800-ft diffuser. Density stratification of the receiving water is not as pronounced south of the bar as inside the bar, and the effluent will rise to the surface so long as the dilution is not greater than about 16 to 1. On this basis the diffuser will have 10 ports, each 21 inches in diameter, discharging horizontally. Soil conditions in the area are stable, and the pipeline may be constructed in or laid directly on the natural bottom. Estimated contract cost is $11.0 million, and total project cost is $16 million.

Option 7b, Outfall Performance. Surface advection away from the proposed outfall site during the wet weather season is southerly, approximately parallel to the shoreline. While the magnitude of the displacement vectors is less than for

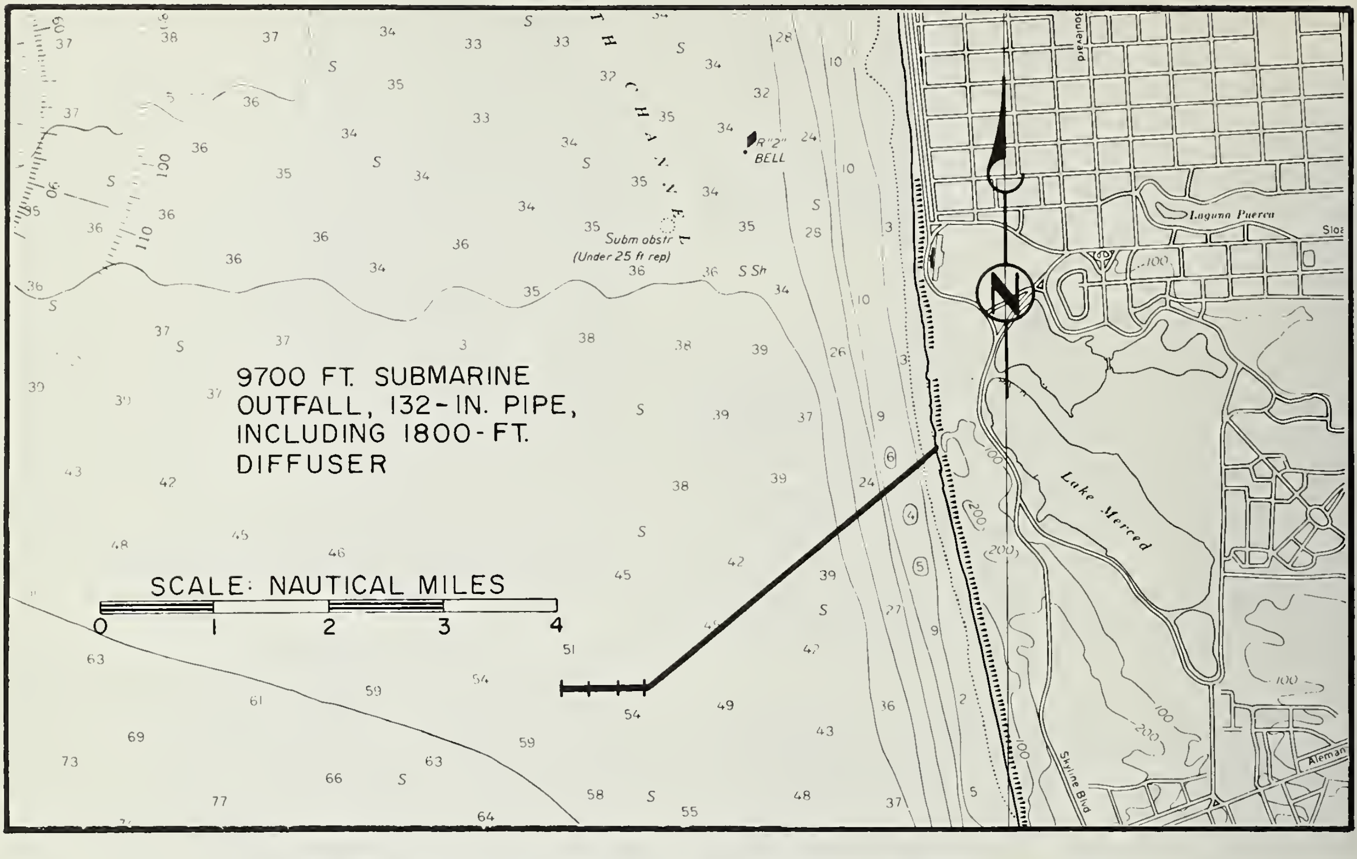


Fig. 7-16 Richmond-Sunset Zone, Wet Weather Disposal Option 7B

the area inside the bar, displacement is positive and of sufficient magnitude that a buildup of waste concentration will not occur.

Initial dilution in the rising waste plumes will be 16 to 1, and the width of the discrete surface fields will be about 100 ft. Subsequent dilution due to horizontal dispersion will increase the dilution to 50 to 1 by the time the discrete fields merge 18 minutes after release. An additional 2 to 1 dilution of the merged field will require 110 minutes, giving a total time of about 2 hours and 10 minutes to reach a dilution of 100 to 1. Again, it is pointed out that this analysis ignores dilution due to vertical dispersion. A greater dilution can be achieved in less time by increasing the length of the diffusers, but this does not appear to be warranted.

The oceanographic information does not indicate that the field will move toward shore, but after four to six hours the diffused edges of the field may begin to contact the shoreline south of the discharge site. The accuracy of diffusion predictions after that length of time is open to some question, but it is possible that the dilutions along the shoreline may be between 500 and 1000 to 1. Considering the intermittent nature of the discharge and the uncertainty of the calculation, the expense of extending the outfall seaward in order to avoid this possible shore contact does not seem to be warranted. Before a major outfall is built in that area, however, more information on surface field movement should be collected.

Treatment Required for Wet Weather Flow

All intermittent wet weather flows will require treatment for substantially complete removal of gross settleable and floatable material. For disposal in the manner described above, no further treatment is required to protect the marine environment. Wet weather discharges to the surface inside the bar will probably require chlorination to achieve a 99.9 percent reduction in coliforms. Wet weather discharges with high initial dilution inside the bar, and wet weather discharge to the surface in the area south of the bar, will require chlorination to achieve about a 99 percent reduction of coliforms. The Regional Board's attitude toward turbidity, discoloration and maximum initial dilution as opposed to maximum seaward advection will determine whether additional treatment is required.

CHAPTER 8

SUMMARY

Faced with a number of sewerage problems which require careful long-range planning and the expenditure of vast sums of money, the Department of Public Works of the City and County of San Francisco undertook several studies aimed at the development of a master plan for sewage collection, treatment and disposal. One of the important aspects of the master plan is the feasibility of discharging treated waste to the waters of the bay and ocean adjacent to the city as a method of ultimate disposal. In July, 1969 the city engaged the firm of Brown and Caldwell to make the necessary engineering and ecological investigations and prepare a report which would present preliminary designs for submarine outfall sewers to dispose of the city's dry and wet weather wastes in a manner consistent with the requirements and policies of all regulatory agencies.

Many of those who find it necessary to refer to this report will have neither the time nor the inclination to study it in detail. For their benefit this chapter summarizes the essential facts and presents concisely the conclusions of the study.

EXISTING SEWERAGE SYSTEM

The first sewers were constructed in San Francisco about the year 1850, and by about 1910 the city was served by a planned system of trunk sewers and interceptors, most of which are still in service today. The trunk sewers were designed to carry both sanitary sewage and storm water and were run by the most direct route to the waterfront, where the wastes were discharged raw into the bay and ocean. The first of the city's three sewage treatment plants was placed in operation in 1938, and the remaining two were completed in 1951.

The entire city is divided into three sewerage areas, each of which is identified by the name of the primary treatment plant which serves the area. Present mode of operation provides for interception, conveyance and treatment of sewage flows up to about three times the average dry weather flow. Flows in excess of that amount are bypassed directly to the receiving waters at 15 principal points around the perimeter of the city.

The Richmond-Sunset Water Pollution Control Plant was constructed in 1938 in the western end of Golden Gate Park. The plant has a peak hydraulic capacity of 70 mgd, presently treats an average dry weather flow of about 20 mgd, and serves the entire western slope of the city. Chlorinated effluent from the Richmond-Sunset plant is discharged to the ocean shoreline through a tunnel which terminates at Lands End.

The North Point Water Pollution Control Plant serves the main downtown section of San Francisco. Completed in 1951, it has a peak hydraulic capacity of about 160 mgd and is presently treating an average dry weather flow of 60 mgd. The installed pumping capacity at the plant is 190 mgd. After chlorination the effluent from the North Point plant is discharged to the Central Bay through four 48-in. cast iron outfalls installed beneath Piers 33 and 35.

The Southeast Water Pollution Control Plant is designed for a peak flow rate of 70 mgd and presently treats an average dry weather flow of 18 mgd. Also completed in 1951, the Southeast plant serves the principal industrial area of the city and also processes the raw sludge which is pumped from the North Point plant. The chlorinated effluent is pumped to a submarine outfall with a 300-ft diffuser section located in 40 ft of water about 800 ft offshore of the Army Street terminal.

Sewage flows resulting from rainfall in excess of 0.02 inches per hour are presently bypassed directly to the bay and ocean. The Regional Water Quality Control Board has declared the present practice to be unacceptable, and the city has included the problem of storm water containment and treatment in its master plan studies.

SEWAGE DISPOSAL REQUIREMENTS AND METHODS

Disposal of sewage and industrial wastes from the City of San Francisco is regulated by Regional Water Quality Control Board No. 2. The Regional Board sets discharge requirements for regulation of specific discharges and establishes long-range policy goals for the regulation and improvement of water quality within its region. In authorizing this study the Director of Public Works stated that the recommendations of this report must comply not only with the requirements and policies of the Regional Board, but also with the water quality objectives of the Bay-Delta Water Quality Control Program. The Regional Board's requirements and the policy goals of all agencies have two objectives: the protection of public health and the protection of the beneficial uses of the receiving waters.

Requirements for Disposal to Central Bay

Briefly summarized, the dry weather disposal requirements and policy statements of the Regional Board for disposal of liquid wastes to the Central Bay are as follows:

1. The plant effluent must show substantially complete removal of settleable and floatable matter, and must be diluted as it enters the receiving water to 10 percent or less of the 96-hr TLm. TLm denotes median tolerance limit, which is the waste concentration, expressed as a percentage, at which half of the test organisms die in the stated time.
2. The receiving water must be free of floating, suspended or deposited matter or objectionable aquatic growth caused by the waste discharge, and must not be appreciably altered in temperature, turbidity or color.
3. Dissolved oxygen near the surface of the water must be at least 5.0 mg/l, and the pH must be between 7.0 and 8.5.
4. The median coliform count must not exceed an MPN of 240/100 ml, which is a value that is recognized as suitable for salt water bathing.

Disposal requirements for wet weather overflows are practically the same as for dry weather with two exceptions. The goal for settleable matter in wet weather overflows is slightly less restrictive than for dry weather, but the requirement for toxicity is 75 percent survival of test organisms in the undiluted waste, which is more restrictive than the dry weather requirement. All of the present wet weather overflows are in violation of requirements.

Requirements for Disposal to the Pacific Ocean

Policy statements by the Regional Board which will strongly influence plans for ocean disposal of San Francisco wastes include the following:

1. No policy objective has been established for bacteriological quality of water more than 1000 ft seaward of the shoreline.
2. For nearshore waters the bacteriological requirement is an MPN of 1000/100 ml or less on 80 percent of the samples, except that at beaches protected for shellfishing the median MPN is 70/100 ml.
3. The mean annual dissolved oxygen level is 6.0 and the minimum for a single sample is 5.0.
4. No waste discharge shall produce bottom deposits, odors, floating material or significant variations in temperature, salinity, turbidity or color.
5. Toxicity must not adversely affect aquatic life or wildlife, and nutrients from the waste must not cause abnormal biotic growths.

Bay-Delta Policy Objectives

In some respects the policy objectives of the Bay-Delta Program are more stringent than those of the Regional Board. Those cases are cited below.

For San Francisco Bay:

1. The dissolved oxygen objective is a median of 7.0 mg/l and a 95 percentile of 6.0 mg/l.
2. The coliform objective is a median MPN of 70/100 ml for the entire bay.
3. The minimum recommended dilution for any waste at any point is 25 to 1.
4. For floatable materials, the objective is 20 mg/sq m for the surface of the receiving waters, and 300 mg/sq m for shore areas.

For the Pacific Ocean:

1. Initial dilution of the waste stream must be 100 to 1 median and 80 to 1 minimum.
2. Within one mile of shore the MPN must be 1000 per 100 ml or less in 80 percent of the samples. The MPN at all beaches must be a median of 70 per 100 ml or less.

Federal Water Quality Control Policy

The Federal Government does not exert direct control over waste discharges but nonetheless exercises effective indirect control through its power to withhold construction grants. The most far-reaching federal policy is the recently announced requirement that to be eligible for federal grants a treatment and disposal works must remove 85 percent of the 5-day BOD. This requirement may be waived at the discretion of the Environmental Protection Agency if the waste is discharged to open ocean waters through an outfall in a manner which will not adversely affect the marine environment.

Deep Water Disposal

The capacity of the marine environment to accept sewage effluent and render it harmless is controlled by four basic mechanisms. These are initial dilution, subsequent dilution, disappearance of coliform organisms, and behaviour of local currents. Special attention was given to each of these mechanisms in the oceanographic study program. Computer programs were developed for prediction of the behaviour of jets discharged from a submarine diffuser (initial dilution) and for the dilution of a surface effluent field due to turbulent diffusion into the main water mass (subsequent dilution). The latter program also considers the effect of the die-off of coliform organisms in sea water, which is a well-documented natural phenomenon. The computer programs were verified by comparison with the measured results achieved at the city's Southeast plant submarine outfall.

The fate of settleable and floatable materials released to the marine environment cannot be calculated by the use of diffusion formulas because these materials tend to reconcentrate on the bottom and on the surface. Their behaviour is controlled by currents, mass water movement and wind-induced movement of the surface film, which can be defined only through oceanographic investigations.

PHYSICAL OCEANOGRAPHY

An intelligent prediction of the impact of waste disposal on the marine environment can be made only after the physical and ecological makeup of the environment is understood. The physical oceanographic studies were concerned with the factors of mass water movement, rates of dispersion and the physical and chemical makeup of the water mass. Field work was confined to the particular areas of concern to this study, specifically the Central Bay and the Gulf of the Farallones adjacent to the Golden Gate. The work of other investigators was reviewed and incorporated into this study where appropriate.

Physical Oceanography of Central California Coast

The Pacific Ocean off the coast of Central California has two basic oceanographic seasons, which are (1) the Dry Season when the southerly California Current is the prevailing nearshore current, and (2) the Rainy Season when the northerly Davidson Current interposes itself between the coast and the California Current. The Dry Season current regime may be divided into two periods: (a) the upwelling period of late spring and summer, and (b) the period of no upwelling during the clear hot weather of later summer-fall, or the so-called Oceanic period. Oceanographic field work was planned to define conditions during each of the above periods.

Data Collection Methods

The principal tool used in measuring mass water movement was aerial photography. It was found that the movement of more turbid water out of San Francisco Bay and into the ocean could be tracked visually and photographically by recording the changing position of the advancing turbidity front.

Physical and chemical characteristics of the water masses were determined by measurements from a boat equipped with instrumentation for oceanographic measurements. Measurements of salinity, temperature, dissolved oxygen and water clarity were taken to document existing conditions and to trace the movement of water masses.

A principal source of current information was the data collected by the US Coast and Geodetic Survey in San Francisco Bay and the Gulf of the Farallones in 1952, 1953 and 1954. The USC & GS information was supplemented by measurements made in the course of this study using both in-situ and captive current meters.

The procedure employed in dispersion studies involved the measurement of the rate of dispersion of a quantity of red fluorescent dye dropped in an area where a surface effluent field might logically be dispersed. The data obtained from the measured rate of dye dispersion were analyzed to obtain dispersion coefficients which were used in the computer program for subsequent dilution of an effluent field.

Since movement of particulate matter in the surface water film may be quite different from the movement of the water mass as a whole, a number of measurements were made to define surface drift. The method selected involved the release of old-fashioned cardboard milk bottle caps at various locations and tidal conditions. After the caps had been given time to drift ashore, approximately 20 miles of beaches and shorelines were walked by pickup crews who collected the caps and recorded the location where they drifted onto the shoreline. Further information on surface drift was obtained from the movement of oil released in the major oil spill at the Golden Gate in January, 1971.

Physical Oceanography of the Gulf of the Farallones

Oceanographic investigations over a full year produced information describing the characteristics of the Gulf of the Farallones and the way these characteristics are influenced by the seasons. Within the principal area of investigation, which extends in an arc from Rocky Point on the north past the San Francisco Lightship to Point San Pedro on the south, the overwhelming influence on oceanographic characteristics is the tidal ebb and flow from San Francisco Bay. The actual area which is strongly influenced by tidal ebb and flow varies with the season of the year, being greatest during the season of high fresh water outflow and smallest during the season of lowest fresh water outflow.

Mass Water Movements. The ebbing tide from San Francisco Bay moves strongly westward and southward on the surface into the Gulf of the Farallones. During the months of high fresh water outflow the water mass is strongly layered, with the surface layer of much lower salinity than the bottom layer, and the surface ebb lasts longer than the flood. During maximum fresh water outflow the surface flow may ebb continuously.

The distance to which the surface mass moves westward and southward is a function of tidal amplitude and degree of layering. With maximum fresh water outflow and maximum tidal amplitude the bulb of surface outflow may reach westward almost to the Farallon Islands and southward past Point San Pedro. Even under summer conditions of minimum layering and minimum tidal amplitude the ebbing tide reaches southward to Lake Merced and westward to the main shipping channel.

Once the ebbing surface layer has reached its maximum excursion, it moves comparatively little until moved along by the next ebb. The water which enters the bar on the flood tide comes primarily from the north and south nearshore. This pattern results in a predominant inflow of dense, saline water on the bottom and a predominant outflow of less saline water on the surface, producing a high rate of tidal exchange through the Golden Gate.

Physical-Chemical Characteristics. The water mass characteristics of particular concern in planning for a submarine waste discharge are water density, dissolved oxygen content, and clarity. Water density data show that an effluent discharge outside the bar to the west will remain submerged throughout the year. Inside the bar an effluent field will remain submerged during much of the year but will surface occasionally during the summer and fall. Outside the bar to the south an effluent field will remain submerged most of the time, but the total number of observations is insufficient to guarantee year-round submergence.

Dissolved oxygen content of the surface waters outside the bar is generally near saturation, but the bottom layer has values as low as 4.0 mg/l during the upwelling season. Dissolved oxygen values inside the bar are lower in the summer and fall than the waters outside the bar, and are generally more representative of Central Bay water than ocean water.

Water clarity in the Gulf of the Farallones varies diurnally and seasonally. Secchi disc readings ranged from a low of 1.5 ft inside the bar in February to a high of 26 ft outside the bar in October.

Currents. Maximum currents occur during the season of high fresh water outflow, and the strongest currents occur closest to the mouth of the Golden Gate. Outside the bar bottom currents are small and surface currents seldom exceed one knot.

Dispersion Coefficients. Altogether, over 50 separate calculations of dispersion coefficients were made from field data collected in the Gulf of the Farallones. The rate of dispersion was found to correlate strongly with scale but not with any other environmental factor such as current, wind, wave height, etc. The relationship adopted for use in this study was $k=20\ L^{4/3}$, which indicates a rate of dispersion several times higher than other observers have reported for the open ocean condition. This may be postulated to result from a higher level of turbulence created by massive tidal flows through the Golden Gate.

Surface Drift. Analysis of the results of two quantitative surface drift studies, involving 30,000 cardboard discs released at five stations in the Central Bay and Gulf of the Farallones, produced several important conclusions:

1. Floatables discharged in the Central Bay in the vicinity of Alcatraz will not accumulate on the bay shoreline in significant quantities.

2. Floatables released outside the Golden Gate will not enter the bay.

3. The heaviest accumulation of floatable material from outfall sites reasonably available to the City of San Francisco will occur on beaches south of the Golden Gate.

Floatables released at or near any of the available sites may be expected to accumulate on the shoreline at a rate of 1.6 percent per mile south of the Golden Gate from Point Lobos to Point San Pedro and 0.4 percent per mile north of the Golden Gate from Point Bonita to the Bolinas Peninsula.

Physical Oceanography of San Francisco Bay

Because of its hundred-year history as a major port, San Francisco Bay has received vastly more attention from oceanographers than the Gulf of the Farallones. Currents in particular have been studied in detail, and these studies have shown that the basic flow patterns remain unchanged throughout the year despite some seasonal modifications.

Currents and Mass Water Movement. The pattern of mass water movement in the Central Bay adjacent to the City of San Francisco is well defined. On the flood tide water flows through the Golden Gate, parallels the San Francisco shoreline through the channel between North Point and Alcatraz, passes under the Bay Bridge west of Yerba Buena Island, and flows southward into the South Bay. On the ebb tide the water reverses direction and retraces its course. As a rule surface currents are swifter than bottom currents and ebb currents are swifter than flood currents.

Under wet weather flow conditions the Central Bay and the South Bay, at least as far south as Hunters Point, show a net seaward movement on the surface and a net bayward movement in the bottom layer. This seaward displacement is especially pronounced in the Central Bay, indicating that the mean residence time of a surface waste field discharged to the Central Bay in wet weather would probably be less than 12 hours.

Oceanographic data obtained during dry weather indicate that net seaward displacement of the surface layer persists in the Central Bay even during the periods of minimum fresh water outflow. However, in dry weather the magnitude of the phenomenon is much reduced.

Dispersion Coefficients. Dispersion coefficients for the Central Bay were determined in the same manner as described for the Gulf of the Farallones, and the rate of dispersion was found to be even higher than in the gulf. The relationship adopted for use in the Central Bay was $k=33\ L^{4/3}$, which is an order of magnitude higher than other observers had found valid for open ocean conditions.

Physical-Chemical Characteristics. Massive density stratification exists in the Central Bay during high fresh water outflow, but has largely disappeared by April. Throughout the summer and fall there is little change in the degree of stratification, and occasionally complete vertical mixing occurs. Dissolved oxygen at the surface remains consistently about 7.0 mg/l, and the minimum values measured at depth was 6.0 mg/l. Water clarity is lowest during the winter season, when a minimum Secchi disc reading of 0.6 ft was recorded in the Central Bay. Secchi disc readings for the summer and fall are generally greater than 3 ft, with a measured high value of 10 ft.

Surface Drift. As described previously, surface drift studies show that floatables released in the Central Bay will not be deposited on the bay shoreline. This observation was confirmed by the results of the massive oil spill in the Central Bay in January, 1971. Little or no oil was reported on the shoreline bayward of the point of release.

Special Oceanographic Studies

Two special oceanographic studies were undertaken. The first measured performance of the city's two major outfalls, and the second measured the amount of new ocean water brought into the Central Bay by the mechanism of tidal exchange.

The outfall performance studies measured initial and subsequent dilution at the city's North Point and Southeast outfalls and compared the results with the values predicted by computer analysis. The results verified the accuracy of the computer programs. Initial dilutions at North Point were as low as 3 or 4 to 1 right over the discharge, but reached 20 to 1 in 50 ft, 100 to 1 in 2-3000 ft, and 1000 to 1 in 6-7000 ft. At the Southeast plant the minimum measured dilution was 53 to 1, reaching 1000 to 1 after a mile and 10,000 to 1 in two miles. The effluent fields were found at times to be visible in dilutions between 500 and 1000 to 1.

Using chlorides as a tracer, the amount of new water which enters the bay by the mechanism of tidal exchange was measured for two different tidal conditions. The median value for tidal exchange in dry weather was found to be 24 percent of the tidal prism, which brings approximately 24 billion cubic feet of new water into the Central Bay during each 25-hr tidal cycle. Fresh water outflow which results in significant stratification increases the measured value.

ECOLOGICAL INVESITGATIONS

Ecology is defined as the total relationship of an organism to its environment. When properly understood, the environment can be protected and still managed in such a way that man's interests and the conservation of nature are balanced. The disposal of large volumes of sewage effluent to a marine environment creates a potential for large scale environmental change, and ecological investigations are essential to insure that detrimental changes will be avoided.

The ecological phase of the marine waste disposal study had two objectives: (1) documentation of existing conditions in areas which might be affected by proposed San Francisco waste discharges, and (2) prediction of the ecological effect of the proposed discharges. The work program developed to achieve the study objectives included a review of all literature related to marine resources in the San Francisco area, a field investigation of the marine environment, and a laboratory investigation of the response of marine organisms to dilution of San Francisco liquid wastes.

Field Investigations

Biological field investigations were conducted in San Francisco Bay and the Gulf of the Farallones from December 1969 through December 1970. The investigations included plankton studies, benthic studies, diving studies, intertidal studies and in-situ cage experiments.

Plankton Studies. Plankton are the tiny floating plants and animals which fill the role of primary producers and form a vital link in the marine food chain. Many larger organisms, including Dungeness crab, start out as larval stages in the plankton. The plankton sampling and analysis program was undertaken jointly by Brown and Caldwell and the California State Department of Fish and Game. A total of 85 samples were collected from the Gulf of the Farallones at depths of two meters and 10 meters.

Only three Dungeness crab larvae were identified in the plankton samples, though the larvae of other crabs were often abundant. No explanation is offered for this low figure. Frequent fluctuations in plankton numbers and diversity occurred during the sampling program, many of which could be related to changes in the physical environment. During periods of upwelling the ocean stations exhibited a shift in dominant species and an increase in plankton numbers. During the period of high fresh water runoff the non-motile plankters were scarce, and there was consequently a reduced species diversity.

Benthic Studies. Benthic organisms are those life forms which grow on or in the bottom materials in an aquatic environment. Their lack of mobility makes them subject over much of their life cycle to the environmental characteristics at a single location, and they are therefore generally regarded as effective indicators of environmental stress.

Analysis of the benthic samples demonstrated that there are four types of benthic communities within the study area. Named for their general location, these are called the Shelf, Near Reef, Bar, and Bay communities. The Near Reef community has the highest diversity and productivity, while the Shelf community was lowest in both categories. The Bar community was characterized by changing patterns of predominant taxa and productivity. The Bay community lives in an area with high mud and silt fractions in the sediments and has low diversity.

Few economically important species were identified in any community. Almost all juvenile Dungeness crabs came from the Bar and Near Reef communities, but even there the number was small.

Diving Studies. Four nearshore locations were studied by biologist-divers to evaluate the marine biota at specific locations in San Francisco Bay the Gulf of the Farallones. The four locations selected were Lands End, Point Bonita, Muir Beach and Piers 33 and 35 in San Francisco Bay. The first and last points are influenced by the discharges from the Richmond-Sunset and North Point Water Pollution Control Plants, respectively.

The Muir Beach transect yielded more species of plants and animals than any other station. Point Bonita had about 80 percent, Lands End 60 percent and Piers 33 and 35 15 percent of the Muir

Beach total. All three ocean stations displayed a well-developed faunal composition, but the flora was somewhat deficient, probably because of turbidity. The effect of the Richmond-Sunset outfall was very localized and resulted in little or no reduction of subtidal species diversity. The North Point effluent discharge affected the biota within 200 ft of the outfall, but it was difficult to separate effluent effects from other environmental factors such as wave exposure, fresh water effects and substrate influences.

Intertidal Studies. Seven intertidal areas were investigated, including Gashouse Cove, Lands End and Point Bonita, all of which are influenced by fresh water outflow, and Duxbury Reef, Rocky Point, Rockaway Beach and Moss Beach, all of which are mainly oceanic in composition. Duxbury Reef and Moss Beach contained the highest diversity of plants and animals, while Gashouse Cove Supported the lowest diversity. The influence of the outfall on the intertidal biota at Lands End could not be observed more than 400 ft from the point of discharge.

In-Situ Bioassays. An attempt was made to assess the toxic effect of the North Point effluent by suspending fish in cages in the effluent field. Test results indicated there was no significant toxicity to three-spined stickleback resulting from the North Point effluent field. There was some evidence that bay water along the San Francisco shoreline was more toxic than at the Horseshoe Bay control site. The source of this apparent toxicity was not identified.

Laboratory Investigations

A laboratory research program was carried out at Fort Baker on Horseshoe Bay to develop through controlled experiments quantitative information on the toxicity of San Francisco sewage effluent to marine organisms. Dilution water used in the studies was obtained by submersible pump from the pier at the mouth of Horseshoe Bay. It was representative of Central San Francisco Bay water and was non-toxic to all of the organisms studied. Sewage effluent was collected at each of the city's treatment plants over a 24-hour period and then composited in proportion to the wastes discharged by the city as a whole.

Tests were conducted on many hundreds of organisms from 22 different species representing the littoral, planktonic, pelagic and benthic communities. The tests covered larval, juvenile and adult organisms.

Static Bioassays. Static bioassay tests were used to measure toxic response of juvenile and adult fish and invertebrates to dilutions of San Francisco sewage effluent. These 96-hour tests measured acute toxicity by means of mortality in dilutions ranging from pure effluent to 1:200 effluent water.

Seven species of fish and ten invertebrates were tested in static bioassays. The most sensitive fish was the sculpin, which required 1:20 dilution to assure 90 percent survival for the test period. Of the invertebrates, the most sensitive species was the bay shrimp, which required dilutions greater than 1:100 to insure 90 percent survival. The high toxicity response of bay shrimp, however, was difficult to separate from a general low tolerance to laboratory experimentation. The second most sensitive invertebrate was the sand crab, which required dilutions of 1:20 for 90 percent survival. In no case could significant toxic response be demonstrated after 96 hours exposure in dilutions greater than 1:100.

Environmental Chamber Experiments. Bioassays of small organisms, including eggs and larvae of Dungeness crab, were conducted in the rigorously controlled climatic conditions of an environmental chamber. The egg hatching studies showed a toxic effect at a dilution of 1:50 but a stimulatory response at 1:100. Tests on larvae of Dungeness and sand crabs showed a toxic effect at dilutions less than 1:50 and a stimulatory response at greater dilutions.

Continuous Flow Bioassays. In continuous flow bioassay techniques new background water or a controlled effluent dilution was regularly supplied to the test organisms. This procedure more accurately models the natural environment. Tests were conducted for 96 hours with three-spined stickleback and first stage Dungeness crab zoea, using effluent dilutions of 1:100 and 1:50. The results indicated that there was no toxic effect from the effluent in dilutions equal to or greater than 1:50.

Mircocosm Studies. A microcosm is a miniature world which is designed to model an existing ecosystem. A long term microcosm experiment with Dungeness crab was performed by Dr. George Schumann of Marine Associates, San Diego. Under agreement with Brown and Caldwell, Dr. Schumann grew Dungeness crab larvae to adult form in three microcosms. One was a control, and the other two contained San Francisco effluent in dilutions of 1:200 and 1:100. Dr. Schumann found low survival in the control and proportionately higher survival in the two dilutions. He concluded that the sewage effluent did not contain substances exerting either a short or long term effect on crab larvae. In a separate test Dr. Schumann achieved virtually identical results culturing American lobster larvae in bay water and a 1:100 dilution of San Francisco sewage effluent.

Special Studies. In two special studies the blood response of sticklebacks to the bacteria in sewage effluent was demonstrated, and the biostimulatory effect of San Francisco effluent on open ocean water was assessed. The first study showed that dilutions of effluent less than 1:10 exerted a stress on sticklebacks by changing their blood composition. The second study did not document any increase in chlorophyll _a_ concentrations in dilutions as low as 1:20 after four days.

Ecological Recommendations

The recommendations derived from the ecological investigations are presented in three sections. The first section comprises ecological design criteria for discharge of liquid wastes to Central San Francisco Bay and the Gulf of the Farallones. The second section recommends a monitoring program for future waste discharges, and the third section suggests additional field and laboratory investigations for which the need has been indicated by this study.

Ecological Design Criteria. The design criteria derived from the field and laboratory investigations may be summarized as follows:

1. The best location for a discharge in the Gulf of the Farallones is south of the centerline of the Golden Gate.
2. It is ecologically desirable to limit the flow from a single outfall to about 100 mgd unless a degree of treatment is provided beyond conventional primary.
3. The shoreline and shallow water (less than 10 ft) communities should be protected from continuous exposure to effluent in dilutions less than 1000 to 1.
4. The benthic or bottom population should not be continuously exposed to effluent in dilutions less than 500 to 1.
5. The population in the water column should not be exposed to effluent in dilutions less than 200 to 1 on a long term basis or less than 100 to 1 on a short term basis (24 hours).
6. The degree of treatment prior to discharge should be at least equivalent to conventional primary with efficient settleable solids removal.
7. A surface effluent field is desirable for large intermittent wet weather discharges.
8. The outfall and diffuser should be constructed in a manner which will not impede the movement of benthic animals.

Monitoring Programs. In order to document any environmental change that a new marine waste discharge might cause, a comprehensive monitoring program is recommended for any new outfall. A program of considerable scope is necessary because the changes which the program will seek to document will be subtle ones, if they occur at all. Monitoring should begin at least one year before an outfall goes into operation.

Other Investigations. The research program undertaken in connection with this study suggested other avenues of investigation which would contribute to a better understanding of the marine environment surrounding San Francisco. Principal areas suggested for future investigation are:

1. The mechanisms by which municipal effluents affect the metabolic responses of marine organisms.
2. The response of invertebrate eggs and larvae to municipal wastes.
3. Further biological surveys in the Gulf of the Farallones to supplement the sparse available data.
4. Further studies on the ecology, life history and response to pesticides of the Dungeness crab.

Additional studies authorized by the City and County of San Francisco are now under way. These include field plankton surveys and an extended laboratory investigation of the reponse of Dungeness crab to municipal sewage effluents.

DESIGN CRITERIA AND BASIS OF COST ESTIMATES

Before alternative submarine outfall projects can be compared, a set of design and cost criteria must be established which are applicable to all projects.

Design Criteria

Oceanographic and ecological factors which will influence the discharge of liquid wastes to the

Central Bay or Gulf of the Farallones were set forth on the basis of information obtained from the investigations conducted in the course of this study. The ecological design criteria established minimum dilutions of San Francisco effluent which are necessary to insure protection of the marine environment. The recommended dilutions contain a factor of safety of 10 over the minimum dilution which was found to cause detectable adverse effects on the most sensitive organisms. By habitat, the recommended dilutions for long-term exposure are 1000 to 1 for shoreline and shallow water areas, 500 to 1 for the benthic community and 200 to 1 for the surface water. The latter value can reasonably be reduced to 100 to 1 for exposures less than 24 hours.

Information on the location and quantities of waste discharges was obtained from the Department of Public Works. Submarine outfall lines are assumed to be constructed of reinforced concrete pipe with flexible rubber gaskets and installed using the best marine construction practices.

Construction Costs

Construction costs used in this report are based on the actual cost of major outfalls constructed in recent years. Costs are based on an Engineering News-Record construction cost index of 1900, which is expected to be reached in San Francisco during 1972. Cost estimates include 25 percent allowance for contingencies and 16 percent for engineering costs.

INVESTIGATION OF ALTERNATIVE PLANS

A series of alternative flow conditions for both dry weather and wet weather were posed by the Department of Public Works. For each alternative the location, size and cost were established for an outfall capable of disposing of the flow in a manner which will meet the anticipated discharge requirements of regulatory agencies as well as the oceanographic and ecological design criteria established by this study. For convenience, the recommendations are discussed by sewerage zones.

North Point Zone

To meet the time schedule established by the Regional Water Quality Control Board, the City of San Francisco had to undertake design of an outfall to dispose of dry weather flow from the North Point plant before this report was completed. This report therefore presents the basis for design and describes the project as designed.

Dry Weather Flow. The projected future peak dry weather flow from the North Point zone is 200 mgd. Two sites were investigated, and the recommended outfall will lie north of Fisherman's Wharf, extending about 5000 ft into the Central Bay. The outfall will provide a minimum initial dilution of 140 to 1 at a flow of 200 mgd. Analysis of outfall performance indicates that the discharge will meet all ecological design criteria with a wide margin of safety.

With three possible exceptions, the recommended outfall can meet all water quality objectives while discharging an effluent equivalent in quality to the present discharge. The three exceptions are turbidity, true color and the federal requirement for 85 percent BOD removal. No quantitative criteria have yet been established for turbidity and true color, but to be realistic, these criteria must reflect the fact that the effluent field will occasionally be visible regardless of degree of treatment. Inauguration of chemical treatment at the North Point plant in the near future will significantly improve the removal of turbidity.

Wet Weather Flow. It is a basic premise of this report that environmental protection of the Central Bay is best achieved by discharging wet weather flows in a manner which will create a surface effluent field. Seaward advection of the surface layer will then move the field out of the bay in the shortest possible time. If the Regional Board does not approve of this concept, wet weather outfalls must be designed for high initial dilution.

The North Point dry weather outfall, by addition of effluent pumping, can be made to carry the full wet weather flow from the North Point zone in the event that high initial dilution is required. Dilution at the peak flow of 350 mgd would be in excess of 100 to 1. If a separate wet weather outfall is constructed, it may be located at virtually any point along the northern waterfront, with preference given to the most westerly location that is economically feasible.

Treatment of wet weather flows for protection of the environment will require substantially complete removal of gross settleable and floatable material, followed by disinfection. The Regional Board may require additional treatment. With maximum initial dilution a 99 percent reduction of coliforms will be necessary, and with maximum seaward advection a 99.9 percent reduction will be necessary.

Southeast Zone

Since the Southeast zone has a functioning dry weather outfall, no specific recommendations for dry weather discharge were made. However, the discharge sites available to the Southeast zone must be classed as less desirable than those for the North Point zone because tidal flushing is less and the zone is closer to ecologically sensitive shallow areas. There is a significant net seaward advection in the surface layer of the bay adjacent to the Southeast zone, especially in wet weather, and outfalls for intermittent wet weather discharges should be designed to produce a surface field. Treatment required for intermittent wet weather discharges will be the same as for the North Point zone.

Richmond-Sunset Zone

All inter-zone waste transfer plans under consideration by the Department of Public Works involve transfer of wastes into the Richmond-Sunset zone for open ocean disposal. A total of eight basic options were considered, including in most cases one or more alternatives for each option. Table 7-2 summarizes the design and cost figures for submarine outfalls necessary to dispose of the waste flows under each option in compliance with the design criteria established in Chapter 6.

The basic findings for the Richmond-Sunset Zone can be summarized briefly as follows:

1. Shallow water over the south bar limits suitable marine disposal sites to two areas where the water is more than 45 ft deep. The first is inside the bar west of Point Lobos. The second lies in an arc outside the bar to the south and west.
2. Any of the dry weather flow options can be adequately disposed of either inside or outside the bar, but some combinations of dry and wet weather discharge would exceed the receiving capacity of the area inside the bar.
3. No improvement in the present degree of treatment (primary plus chlorination) is necessary to protect the marine ecosystem. If additional treatment is necessary, it will be because regulatory agencies require it for reasons other than protection of the marine environment.
4. There is a strong ecological argument in favor of a surface waste field for intermittent wet weather discharges in the Gulf of the Farallones.
5. All intermittent wet weather discharges will require treatment for substantially complete removal of gross settleable and floatable material. A 99 percent reduction of coliforms will be required for discharges outside the bar and a 99.9 percent reduction for discharges inside the bar.

APPENDIX

APPENDIX A

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APPENDIX B

ABBREVIATIONS

BOD	biochemical oxygen demand
cfs	cubic feet per second
cu ft	cubic foot, cubit feet
deg C	degrees Celsius (formerly centigrade)
deg F	degrees Fahrenheit
fps	feet per second
ft	foot, feet
gpd/sq ft	gallons per day per square foot
hrs	hours; except when designated AM or PM, time is presented on the basis of a 24-hour day.
K	knots (nautical miles per hour)
l	liter, liters
m	meter, meters
mg	milligram, milligrams
mgd	million gallons per day
mg/l	milligrams per liter
mg/sq/m	milligrams per square meter
mi	statute mile (5,280 ft)
ml	milliliter, milliliters
ml/l/hr	milliliters per liter per hour
mm	millimeter, millimeters
MPN	most probable number (of coliform organisms
naut mi	nautical mile (6080 ft)
ppb	parts phr billion
ppt	parts per thousand
sq mi	square miles
TLm	median tolerance limit; defined as the waste concentration, expressed as a percentage, at which half of the test organisms die in the stated time.

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